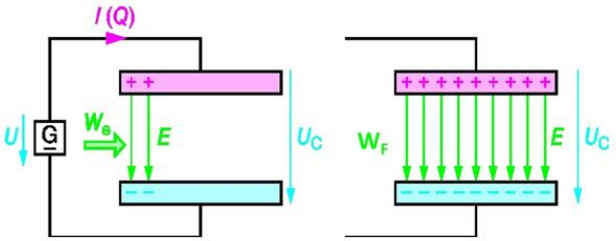

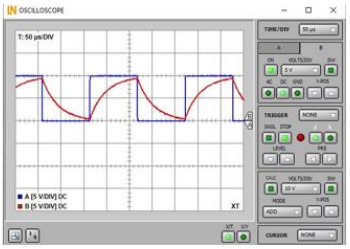

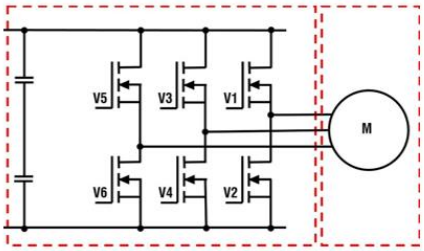

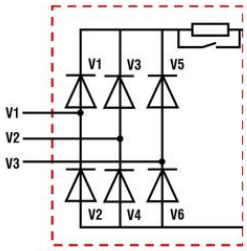

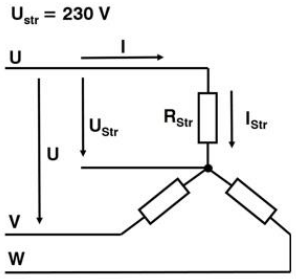

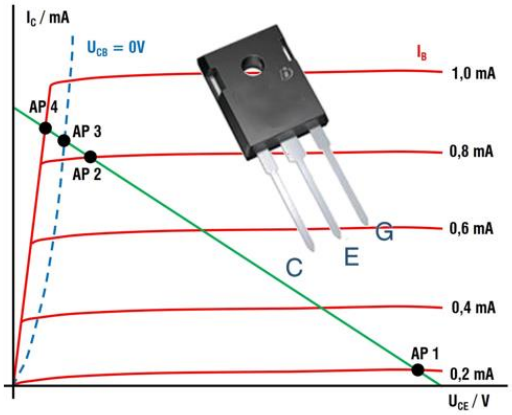

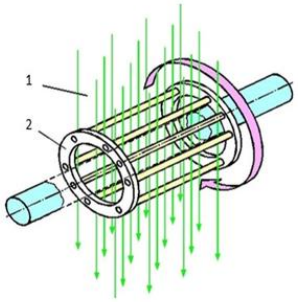

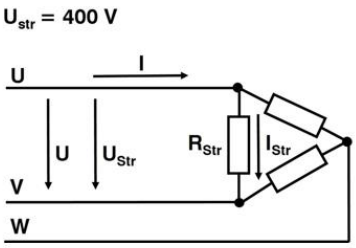

Mercedes-Benz Academy - USA

Mercedes-Benz & Smart, Alternative Drives

Expert for High-Voltage Drive Systems in Motor Vehicles

T2375F-US.TT4
12.02.2025

Mercedes-Benz

This document is intended for training purposes only. The exercises performed in the course cannot simply be implemented in practice without regard to various considerations. Country-specific laws, regulations, and specifications must always be observed.

The document is not subject to ongoing update service. For work on the vehicle, the manufacturer's current workshop tools (e.g. information systems, special tool) must always be used for the vehicle in question.

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Note: For reasons of better comprehensibility, the male and female forms are usually not mentioned. Of course, both genders are always meant.

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1.1 Schedule

Start	07:00	
Breakfast break	Approx. 09:00 am	15 minutes
Midday break	Approx. 11:30 am	60 minutes
Coffee break	Approx. 1:30 pm	15 minutes
End	Approx. 3:00 - 4.00 pm	

(schedule may be different per location or/and audience, example above is for Long Beach Internal Training in 2025)

1.2 Round of introductions

Guiding questions to manage the introduction process:

- Who am I (name)?
- Which company do I work for?
- What are my activities at work?
- What previous knowledge and experiences do I have in the field?
- What training about vehicles with alternative drives have I already attended?

- What are my expectations of the training?

- What are my expectations of the trainer?

1.3 Seminar Rules

- As an important member of the group, I have something important to contribute to this training.
- Equal treatment for all
- Equal rights and obligations for all
- What is said and done in this group stays in this group.
- Everything important is brought into the open. Anything that is not brought into the open is not important and does not matter.
- Let others have their say and don't interrupt
- Limit yourself to what is important and express yourself clearly and concisely. Be brief and concise.
- Agreed times are adhered to
- Introduce experiences on the topic
- Everyone helps to tidy up
- Handle vehicles and tools carefully
- Mobile phone switched to mute or off
- Teamwork during practical work
- Adhere to the safety rules when working on the high-voltage on-board electrical system! If anything is unclear, the trainer should be asked
- The country-specific regulations and rules must be observed.
- Only the prescribed special tools and workshop equipment may be used.
- The required protective equipment must be worn.

1.4 Learning Objectives

- Understanding potential hazards and electrical effect.
- Apply the 5 VDE 0105 safety rules and Mercedes-Benz safety protocols.
- Handle unprotected/faulty HV components safely.
- Use multimeters/oscilloscopes for voltage/current analysis.
- Measure current types; and interpret oscilloscope results.
- Explain voltage/current generation and relationships (Ohm's law).
- Set up and measure group/mixed circuits, voltage dividers.
- Understand purpose, hazards, and methods of potential equalization.
- Use ohmmeters/milliohm meters; explain 2- vs 4-wire measurement.
- Measure and interpret potential equalization in HV vehicles.
- Understand fault current types (frame, short, ground fault).
- Explain safety devices (GFCI, insulation monitors, IT network behavior).
- Diagnose fault current causes using proper devices and procedures.
- Explain delta/star circuits and their effects on voltage/current.
- Calculate and measure electrical output for various current types.
- Describe rectifiers, DC/AC converters, and capacitor functions.
- Know capacitor risks, limits, discharge behavior, and safety checks.
- Test diodes and transistors for function and faults.

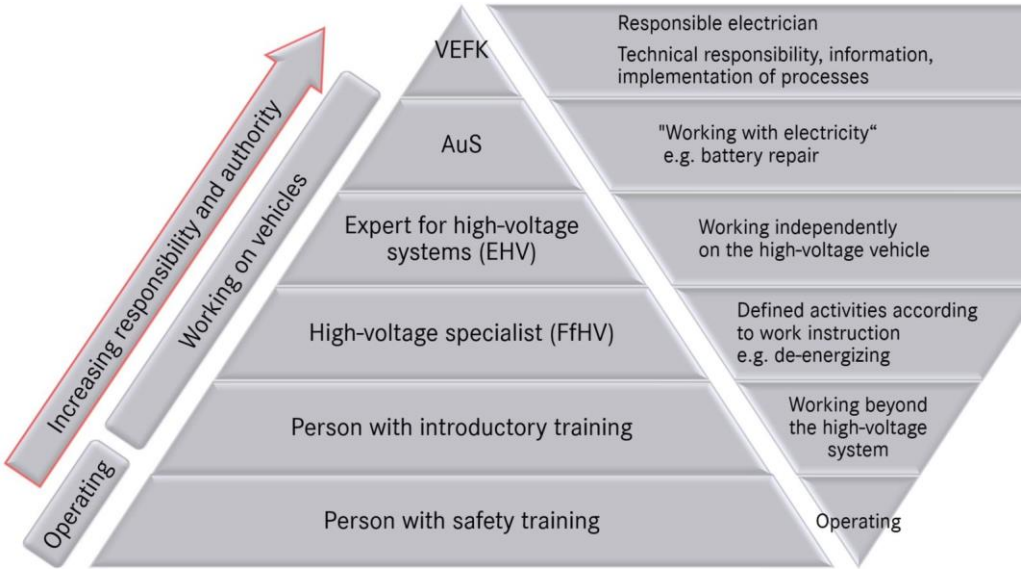
1.5 Greek Alphabet

During the eLearning modules and in your work experienced, you no doubt have come across some Greek letters or words. We must likely are familiar with Alpha, Beta, Pi, lambda to name just a few. Sometimes, there are several different references to the same word, but used in a different area of industry like Medical, Engineering, Physics, etc.

Below you will find the list of the Greek alphabet, that as we go through the course you can reference, and we also provided a space for you to associate an Electrical Engineering association. At the end of the course, we can see how many we used, and you tied an association to.

Capital	Lower-case	Greek name	English
Α	α	Alpha	a
Β	β	Beta	b
Γ	γ	Gamma	g
Δ	δ	Delta	d
Ε	ε	Epsilon	e
Ζ	ζ	Zeta	z
Η	η	Eta	h
Θ	θ	Theta	th
Ι	ι	Iota	i
Κ	κ	Kappa	k
Λ	λ	Lambda	l
Μ	μ	Mu	m
Ν	ν	Nu	n
Ξ	ξ	Xi	x
Ο	ο	Omicron	o
Π	π	Pi	p
Ρ	ρ	Rho	r
Σ	σ	Sigma	s
Τ	τ	Tau	t
Υ	υ	Upsilon	u
Φ	φ	Phi	ph
Χ	χ	Chi	ch
Ψ	ψ	Psi	ps
Ω	ω	Omega	o

2 Safety Rules and Hazards



2.1 Occupational Safety

Occupational safety has the objective of preventing accidents at work and protecting the health of the employees. The employer is obliged to implement suitable measures, means and methods to protect employees against occupational safety and health hazards.

Occupational safety is an important part of our overall responsibility as an company. It is an integral component of our corporate strategy, which is based on increasing value in the long term. Our aim is to shape the working practices so that all employees are fully able to carry out their duties and work safely.

We expect all of our employees to demonstrate readiness and adopt a proactive approach to ensuring safe and health-conscious behavior both at work and outside of work.

2.2 Accident Prevention

Prevention pursues the objective of avoiding accidents at work, occupational illnesses, and work-related health risks. Prevention also means raising knowledge and awareness. Accidents at work and occupational illnesses not only cause physical and mental suffering to those affected, they also cause high costs to businesses.

Everyone is responsible for their own health and safety and also that of their co-workers, by means of:

- Notification of accidents and damage caused to one's health to supervisors
- Notification and (if possible) rectification of any safety and health hazards
- Proper and intended use of devices and machinery and equipment (e.g. a chair must not be used as a ladder)
- Observance of instructions issued by supervisor with regard to accident prevention

2.3 Safety rules

Working on high-voltage systems when live is not permitted as a result of the dangerous voltage and current values. Therefore, any electrical hazard must be excluded before starting maintenance work. These safety rules should be applied in the following conditions:

- Working on defective high voltage systems
- Before removing high voltage components

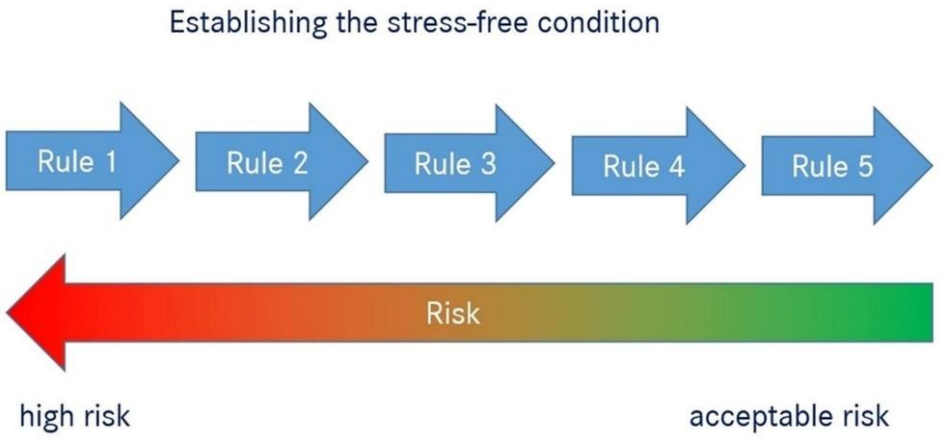
In DIN VDE 0105-100 Section 4.3, the use of an electrically skilled person or an electrically instructed person is mandatory for the implementation of the five safety rules to achieve a safe condition. Section 6.2 of the standard describes the following:

Five safety rules:

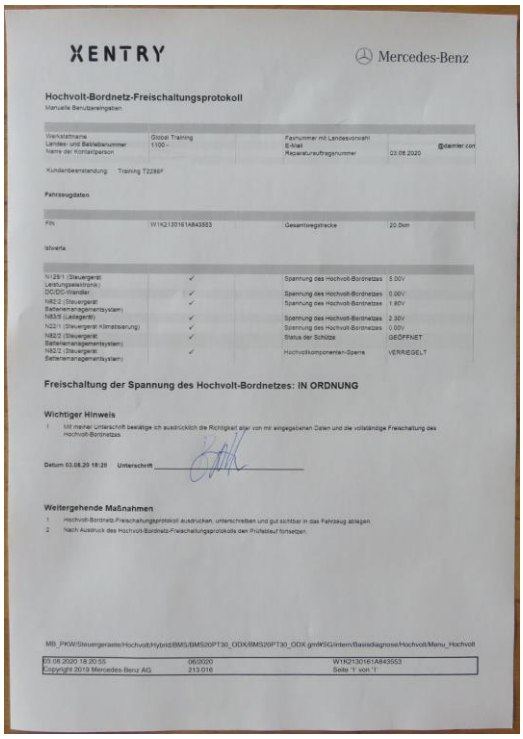
1) De-energize
2) Prevent from being switched on again
3) Determine absence of voltage
4) Ground and short circuit
5) Cover over and place barrier around adjacent live parts

Once all repairs on the high voltage system are completed you are then safe to recommission or reenergize the vehicle. Before doing so you must check for visible damage or obvious faults. It is also important to continue following all safety measures including when working under critical environmental conditions or areas prone to fire/explosion.

Application of the safety rules reduces the risk of electric shock to an acceptable level. The risk line illustrates risk minimization.



The warning sign must be clearly visible on or attached to the vehicle. The condition of the high-voltage on-board electrical system must be documented using the corresponding test log (power disable event log). This log must be stored in the vehicle in a clearly visible location. A warning sign is not provided in Mercedes-Benz Retail operations but can be used additionally.


XENTRY

Mercedes-Benz

Hochvolt-Bordnetz-Freischaltungsprotokoll

Manuelle Benutzereingaben

Werkstattname	Global Training	Fahrnummer mit Landesvorwahl	
Landes- und Betriebsnummer	1100 -	E-Mail	@daimler.com
Name der Kontaktperson		Reparaturauftragsnummer	03.08.2020

Kundenbeanstandung Training T2286F

Fahrzeugdaten

FIN	W1K2130161A843553	Gesamtlaufstrecke	20.0km

Istwerte

N12/9:1 (Steuergerät Leistungselektronik / DC/DC-Wandler)	✓	Spannung des Hochvolt-Bordnetzes	0.00V
N82/2 (Steuergerät Batteriemanagementsystem)	✓	Spannung des Hochvolt-Bordnetzes	0.00V
N83/5 (Ladegerät)	✓	Spannung des Hochvolt-Bordnetzes	1.80V
N22/1 (Steuergerät Klimatisierung)	✓	Spannung des Hochvolt-Bordnetzes	2.30V
N82/2 (Steuergerät Batteriemanagementsystem)	✓	Spannung des Hochvolt-Bordnetzes	0.00V
N82/2 (Steuergerät Batteriemanagementsystem)	✓	Status der Schütze	GEÖFFNET
		Hochvoltkomponenten-Sperre	VERRIEGELT

Freischaltung der Spannung des Hochvolt-Bordnetzes: IN ORDNUNG

Wichtiger Hinweis

1 Mit meiner Unterschrift bestätige ich ausdrücklich die Richtigkeit aller von mir eingegebenen Daten und die vollständige Freischaltung des Hochvolt-Bordnetzes.

Datum 03.08.20 18:20 Unterschrift _____

Weitergehende Maßnahmen

1 Hochvolt-Bordnetz-Freischaltungsprotokoll ausdrucken, unterschreiben und gut sichtbar in das Fahrzeug ablegen.

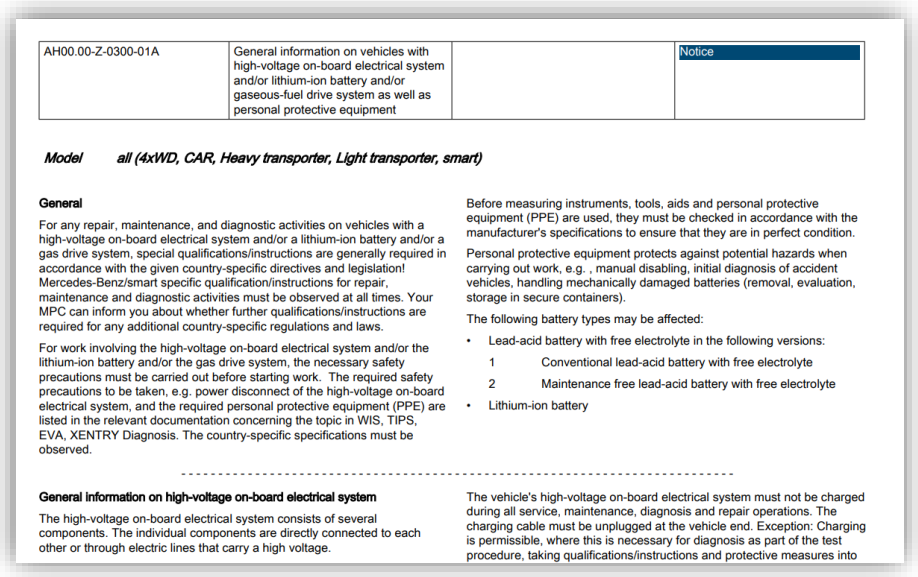
2 Nach Ausdruck des Hochvolt-Bordnetz-Freischaltungsprotokolls den Prüfablauf fortsetzen.

MB_PKW/Steuergeraete/Hochvolt/Hybrid/BMS/BMS20PT30_ODX/BMS20PT30_ODX.gmNSG/Intern/Basisdiagnose/Hochvolt/Manu_Hochvolt

03.08.2020 18:20:55	062020	W1K2130161A843553
Copyright 2019 Mercedes-Benz AG	213.016	Seite 1 von 1

2.4 Mercedes-Benz / Daimler AG safety rules

General instructions for vehicles with high-voltage on-board electrical system and/or lithium-ion battery and/or gas drive system and Daimler AG personal protective equipment are described in document AH00.00-Z-0300-01A.



AH00.00-Z-0300-01A	General information on vehicles with high-voltage on-board electrical system and/or lithium-ion battery and/or gaseous-fuel drive system as well as personal protective equipment		Notice

Model ***all (4xWD, CAR, Heavy transporter, Light transporter, smart)***

General

For any repair, maintenance, and diagnostic activities on vehicles with a high-voltage on-board electrical system and/or a lithium-ion battery and/or a gas drive system, special qualifications/instructions are generally required in accordance with the given country-specific directives and legislation! Mercedes-Benz/smart specific qualification/instructions for repair, maintenance and diagnostic activities must be observed at all times. Your MPC can inform you about whether further qualifications/instructions are required for any additional country-specific regulations and laws.

For work involving the high-voltage on-board electrical system and/or the lithium-ion battery and/or the gas drive system, the necessary safety precautions must be carried out before starting work. The required safety precautions to be taken, e.g. power disconnect of the high-voltage on-board electrical system, and the required personal protective equipment (PPE) are listed in the relevant documentation concerning the topic in WIS, TIPS, EVA, XENTRY Diagnosis. The country-specific specifications must be observed.

Before measuring instruments, tools, aids and personal protective equipment (PPE) are used, they must be checked in accordance with the manufacturer's specifications to ensure that they are in perfect condition.

Personal protective equipment protects against potential hazards when carrying out work, e.g. , manual disabling, initial diagnosis of accident vehicles, handling mechanically damaged batteries (removal, evaluation, storage in secure containers).

The following battery types may be affected:

- Lead-acid battery with free electrolyte in the following versions:
  - 1 Conventional lead-acid battery with free electrolyte
  - 2 Maintenance free lead-acid battery with free electrolyte
- Lithium-ion battery

General information on high-voltage on-board electrical system

The high-voltage on-board electrical system consists of several components. The individual components are directly connected to each other or through electric lines that carry a high voltage.

The vehicle's high-voltage on-board electrical system must not be charged during all service, maintenance, diagnosis and repair operations. The charging cable must be unplugged at the vehicle end. Exception: Charging is permissible, where this is necessary for diagnosis as part of the test procedure, taking qualifications/instructions and protective measures into

Example: AH00.00-Z-0300-01A

For repair, maintenance and diagnostic activities on vehicles with high-voltage on-board electrical system and/or lithium-ion battery and/or gas drive system, special qualifications/instructions are generally required in accordance with the country-specific regulations and legislation. Attention must be paid to the Mercedes-Benz/smart-specific qualifications/instructions for repair, maintenance and diagnostic activities. Your responsible MPC will tell you whether additional country-specific ordinances and legislation must be observed or whether further qualifications or instructions are required.

For work involving the high-voltage on-board electrical system and/or lithium-ion battery and/or gas drive system, the necessary safety precautions must be taken before starting work. The safety precautions to be taken, e.g. disconnection of the high-voltage on-board electrical system, or the personal protective equipment (PPE) required can be found in the relevant documentation on the topic in WIS, TIPS, EVA, XENTRY Diagnosis. The country-specific requirements must be observed.

Measuring instruments, tools, aids and personal protective equipment (PPE) must be checked for perfect condition according to the manufacturer's specifications before they are used. The personal protective equipment protects against potential hazards during work such as manual power disable, initial diagnosis of accident vehicles, handling of mechanically damaged batteries (removal, evaluation, storage in secure containers).

2.5 Safety rules within the Mercedes-Benz Organization

General information has been described in document **AH00.00-Z-0300-01A.**

For repair, maintenance and diagnostic activities on vehicles with high-voltage on-board electrical system and/or lithium-ion battery and/or gas drive system, special qualifications/instructions are generally required in accordance with the country-specific regulations and legislation. Attention must be paid to the Mercedes-Benz/smart-specific qualifications/instructions for repair, maintenance and diagnostic activities.

For work involving the high-voltage on-board electrical system and/or lithium-ion battery and/or gas drive system, the necessary safety precautions must be taken before starting work. The safety precautions to be taken, e.g. disconnection of the high-voltage on-board electrical system, or the personal protective equipment (PPE) required is available in the relevant documentation on the topic in WIS, TIPS, EVA, XENTRY Diagnosis. Country-specific requirements must be observed.

Check measuring devices, tools, equipment and personal protective equipment (PPE) is in perfect working order according to the manufacturer's specifications before use. Personal protective equipment protects during work, such as manual de-energizing.

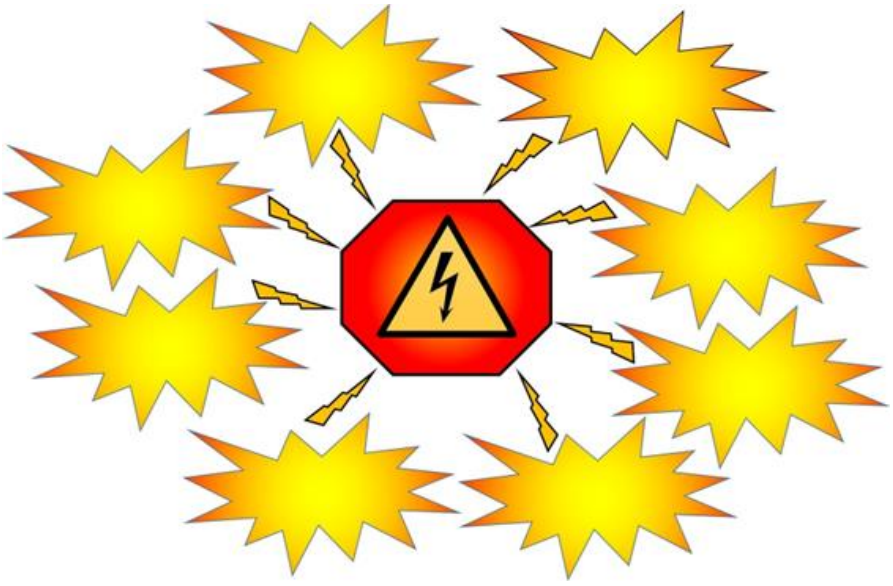
You have to manually disable a vehicle with a high-voltage on-board electrical system.

1) How do you ensure that you use the correct PPE and that it is in perfect working order?

2) Which documents must be observed when working on High Voltage systems?

3) What check must an employee perform before commissioning an electric device?

2.6 Potential hazards



To ensure the safe operation of the electrical system, the protection goal in terms of occupational health and safety includes ensuring that people perform work on electrical systems in low-voltage networks (< 1000 V) in compliance with DGUV Regulation 3.

Traditionally in Mercedes-Benz automotive training we have defined a high-voltage system as being one with greater than 30 V AC or 60 V DC. However, in electrical engineering a low-voltage system is considered up to 1000 V DC or 600 V AC and higher voltage is classified as various other levels such as high-voltage, ultra-high voltage.

As an example, below is a reference to voltage level terminology. Please note, not all countries follow these exactly so there may be some variations:

- Extra low voltage = < 50 V AC < 120 V DC
- Low voltage = 50 – 1000 V AC 120 – 1500 V DC
- High voltage = > 1000 V AC > 1500 V DC

Note: EFK/ES qualified is certified up to 1000 V AC, for higher voltage levels additional qualifications are required (see VDE Rules of Voltage Levels).

Activity:

What conditions could potentially put someone at risk when working around electrical energy?

TR – Print and distribute answer cards, have TN find an image for card, then fill in.

2.7 Effect of electrical hazards

Electrical hazards can cause damage to components or harm to people's health or even death.

What are some possible hazards due to electrical energy?

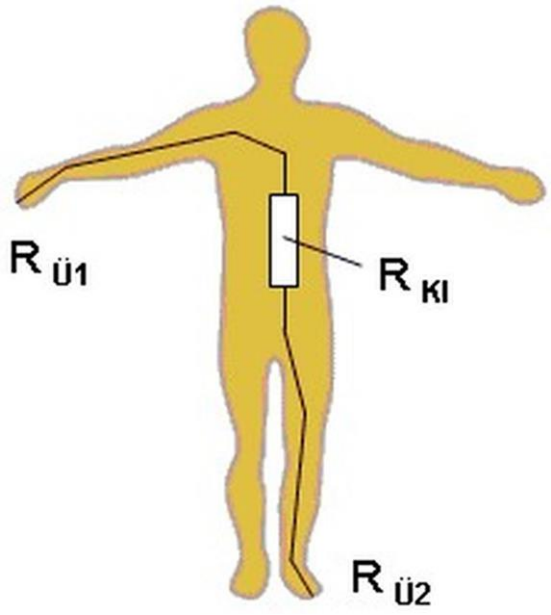
Effect of electrical arcing

The controlled formation of electric arcs is used in engineering, e.g. electric arcs in electric welding (e.g. MIG, MAG, TIG welding). However, electrical hazards can also be caused by an electrical arc when performing non-electrical work in the vicinity of live equipment or using electrical equipment.

If an unwanted arcing occurs as a result of a defect or switching action, it is called an arc fault. Such arc faults occur, for example, in the event of short circuits, damaged insulation of cables or components, and human error. The temperature in an arc fault can be over 4000 °C.

Metal parts then vaporize in fractions of a second and are ejected by the blowing effect of the resulting electromagnetic field.

Typical accident consequences of arc faults are flashing of the eyes by strong UV light and first and second degree burns of the skin.



Resistances of human body

GTT_010282

The resistance of the human body is influenced by the following individual characteristics of the person:

The transition resistance at the current entry and exit points depend on external conditions. Dry clothing and shoe soles have high resistance. If there is moisture, e.g. sweat or a wet floor, the transition resistance is lower, and the current flow is favored.

The average resistance value of a human body is 1000 Ω. Together with the contact voltage, the current intensity can be estimated.

Resistance values of human body		
Longitudinal Flow	Hand - Foot	approx. 1000Ω
	Hand - Feet	approx. 750 Ω
	Hands - Feet	approx. 500 Ω
Lateral Flow	Hand - Hand	approx. 1000Ω
Partial Flow	Hand - Torso	approx. 500 Ω
	Hands - Torso	approx. 250 Ω

An alternating current of just 50 mA can be lethal if it flows through the heart and/or lungs over a period of one second. Due to its frequency, alternating current has a higher physiological effect on humans at the same current strength than that of direct current.

In Europe and many other countries, the household power supply is around 220 – 240 V AC.

In USA and some other countries, the household power supply is half of what Europe uses being it is 110 – 120 V AC.

Calculate the current flowing through 1 kohm resistor at each household power levels mentioned above and note below?

12V DC = _____

110 V AC = _____

220 V AC = _____

Now consider the typical electric vehicle on the market with around 400 V power supply.

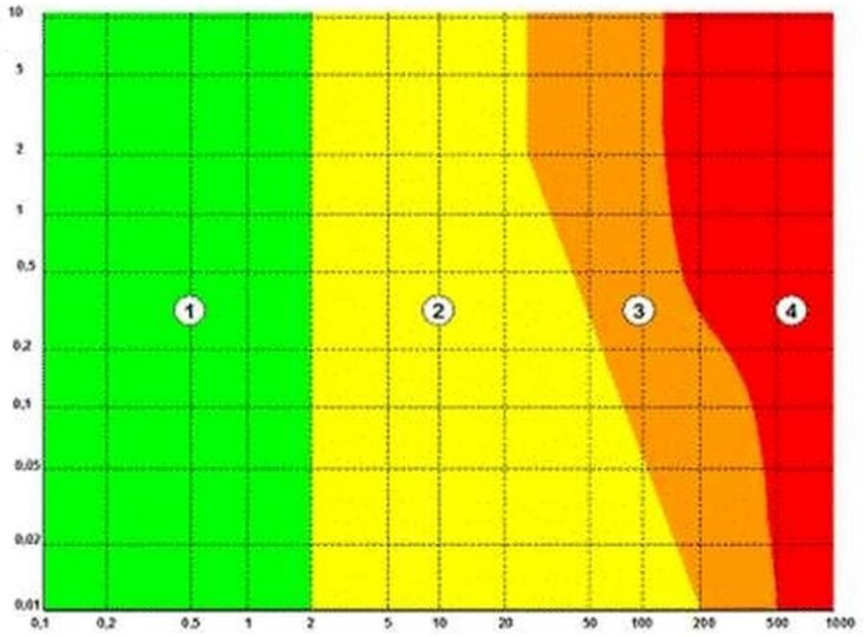
400 V = _____

Current flow through the body

Electric current is increasingly being used to our advantage in medicine. Examples of this would be stimulation current therapy or reactivation of the heart muscle (defibrillation). However, it also creates danger for the human body.

All muscle movements of the human body are triggered by small electrical currents. These pulses are generated in the brain and propagate through the body via nerve tracts - much like currents in electrical conductor tracks. This includes muscle responses, such as in the heart muscle, lung muscle, and almost all other organs. These electrical currents have a voltage of about 50 mV. Applying an external voltage to the body can thus influence the functions of the organs.

Above a certain current strength, it can lead to cramping of the muscles, making it impossible for the person to let go of the point of contact again. Even relatively low current strengths can leave permanent physical damage or lead to death due to a longer exposure time.



*Physical reaction in time-current diagram **Direct voltage** (y-axis: time t in seconds, x-axis: amperage I in mA)* GTT_010280

Range 1 - Perception threshold
Usually no reaction

Range 2
Usually no harmful physiological effects

Range 3 - Release threshold
No organic damage expected, reversible disturbances of pulses in the heart may occur.

Range 4 - Risk of death
Additional severe burns, likelihood of heart fibrillation

In addition to the uncontrollable effects on the muscles, there is a further danger from direct current:

The triggering of a chemical reaction in the body. Particularly with longer exposure times, the blood can be electrolytically decomposed. This results in an "electrochemical electrolysis" of blood components.

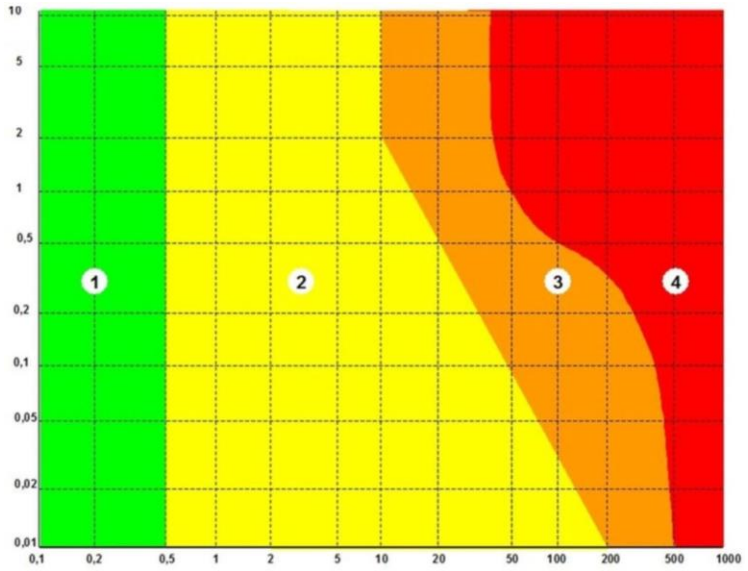
The after-effects may not appear for several days.

For this reason, a physician should be consulted immediately after an accident caused by an electrical voltage, even if there are initially no visible or noticeable signs.

What effect can a Direct Voltage Current have on the human body?

If an alternating voltage is applied to the human body from outside and the resulting alternating current flows through the heart, the heart will try to follow the faster and stronger pulses. It will try to match its beating frequency to that of the electric current.

However, due to its own inertia, this is not possible and cardiac arrhythmias and fibrillation of the heart may occur. The pumping function of the heart fails and thus the blood circulation comes to a standstill. The resulting lack of oxygen in the body causes damage to the brain after only a few minutes. In the further course, this leads to death.



*Physical reaction in the time-current diagram of **alternating current** flowing through the body according to VDE V 0140-479-1 (y-axis: time t in seconds, x-axis: current intensity I in mA)*

Range 1:

No effects and reactions up to the perception threshold.

Range 2:

No adverse physiological effects up to the release limit.

Range 3:

No organ damage is to be expected, but reversible disturbances in the heart with increasing current strength and exposure time. These include atrial fibrillation and temporary short-term cardiac arrest. Muscle contractions and breathing difficulties are likely with prolonged exposure time above the release limit.

Range 4:

Fibrillation of the heart is likely. With increasing current intensity and exposure time, pathophysiological effects such as cardiac arrest, respiratory arrest, and severe burns.

Activity:

Is time a factor that needs to be considered for an electric shock of a current of 1 ampere?

_____

What is the recognized / communicated electric current threshold that a human can typically have no ill effects after current is no longer flowing?

_____

Are the current and time range thresholds for electric shock the same for AC & DC?

_____

What factors will determine the severity of the injury with current flow through the body?

Just as in electrical circuits, the electric current flowing through a body follows Ohm's law. This means that it depends on the applied voltage and the resistance of the human body. In electrical engineering terms, this body resistance is made up of a series circuit of the internal resistance of the human body and the transition resistances at the current entry and exit points.

Secondary accidents

Electricity accidents in the low-voltage range (electricity in the home, office or workshops) often lead to "secondary accidents".

The electric current flows through the human body only for a short time in a range of current strength in which theoretically any length of exposure is still harmless. However, defensive or startle reactions caused by jerky contraction of the musculature can result in accidents such as:

- Falling into a work pit
- Bumping against hard objects
- Scraping or cutting on sharp metal edges due to quickly withdrawing the hand from the danger zone
- Falling from scaffolding or roof workstation (CV)

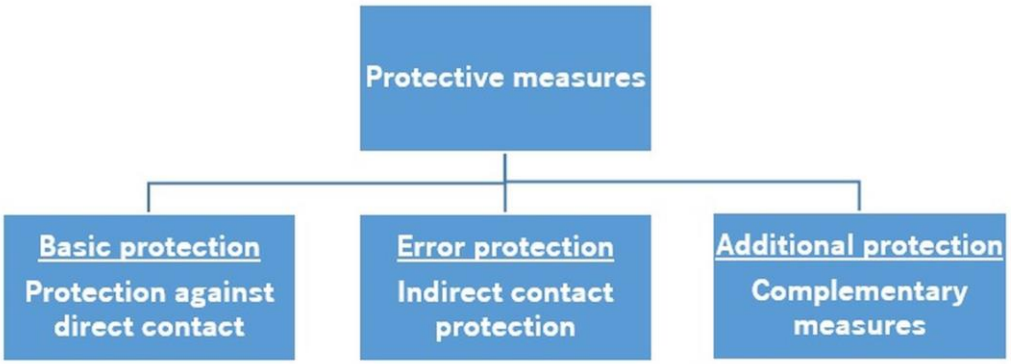
Also, consider the reaction times of humans, these vary by individuals and the type of stimulus the reaction needs. For example, catching a ball will be different to an electric shock!

Most humans take perhaps around 200 – 300 ms to react. Internet has lots of data on studies conducted and different scenarios.

One research on PBS Newshour even posted this finding !

2.8 Safety precautions

When using electrical equipment, an electrical hazard must always be assumed. The risk of danger increases with the likelihood of damage due to external influences and with the level of the electric current.



Safety precautions

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For this reason, measures to protect against electric shock must be defined and implemented by the employer as part of the hazard assessment.

In the case of basic protection, the protection class determines how securely the active parts are protected against contact, penetration of foreign bodies and water, as well as shock resistance (housing protection). It indicates the suitability of electrical equipment for various environmental conditions, in addition to the protection of people against potential hazards during their use.

What are some safety measures implemented in our high voltage vehicles?

2.9 Fault protection

If the basic protection fails, the second protection level takes effect and the fault protection ensures that there is still no risk of electric shock. Devices that ensure fault protection can also cover significant parts of the risk originally reduced by basic protection if the basic protection fails. These residual current devices (RCD) include:

Overcurrent protection devices

Overcurrent protection devices are protective mechanisms in electric circuits, such as one-time-use fuses and automatic circuit breakers, which can be switched on again after tripping. This is primarily concerned with equipment protection. The activation threshold of overcurrent protection devices is sometimes very high. Their task is to protect lines from damage that can result from excessive heating.

Ground fault circuit interrupter

The ground fault circuit interrupter is also sometimes known as an “RC” “D” or residual current device. It provides protection against electric shock and primarily serves to protect people. For humans, currents in the two-digit mA range can be life-threatening.

In the fault current range ≤ 30 mA, its purpose is personal protection. A GFCI that will interrupt the circuit to the load when the ground-fault current is 6 mA is intended to be used in circuits where the line-to-line voltage is 240 V or less

In the fault current range > 30 mA, the ground fault circuit interrupter is for device protection (up to 500 mA).

Fault current sensor

A fault current sensor monitors the insulation status in vehicles. It reports when the insulation resistance falls below a minimum value. This occurs in the event of a fault. If the insulation fault current is exceeded, either only a warning is issued or the high-voltage system is also switched off.

Stationary electrical equipment

This is permanently attached equipment or equipment without a carrying device whose mass is so heavy that it cannot be easily moved. This also includes electrical equipment that is temporarily fixed and operated via movable connection lines. This stationary electrical equipment must have protection through automatic disconnection of the power supply. This automatic shutdown must intervene in the event of a fault current of ≥ 30 mA.

2.10 Personal protective equipment

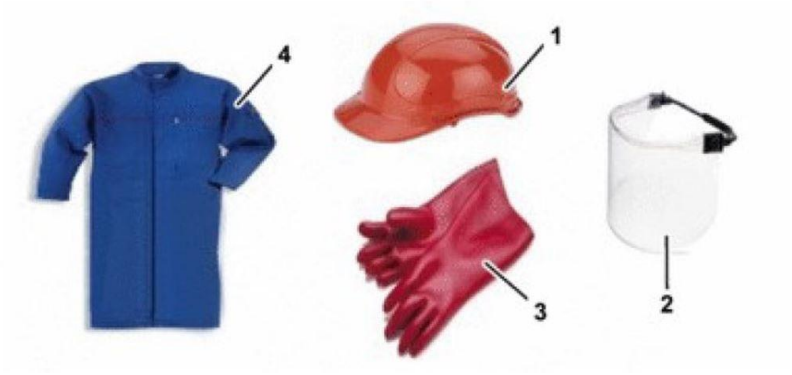
Personal protective equipment PPE is any equipment intended to be used or worn by employees to protect themselves against a hazard to their safety and health, as well as any additional equipment used with the same aim and connected to the personal protective equipment. It must be used for all work and activities which, due to their nature, could cause injury or health impairment and which cannot be prevented by other measures (technical or organizational).

Personal protective equipment (PPE) for work on high-voltage vehicles or batteries

Potential hazards are:

- Electrical hazards due to electric shock, e.g. if contact protection is no longer present
- Hazards posed by arcing in the event of a short circuit or when connector couplings are disconnected

The personal protective equipment (PPE) for high-voltage listed below is the minimum requirement specified by Mercedes-Benz/smart. The country-specific requirements must be observed!



Personal protective equipment

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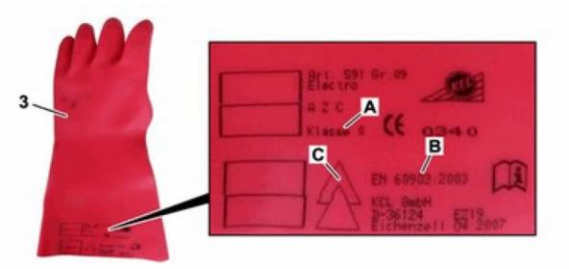
1	Electrician's safety helmet without ventilation holes, according to standard EN 397	**3**	Protective gloves, according to standard EN 60903.2012: Class 0, color red, (marking A (acids), A+H (acid and oil) or R (acid, oil, ozone))
2	Face protection/eye protection, according to standard EN 166	**4**	Arc-flash jacket of Class 2, according to EN/ISO 11612



PPE marking

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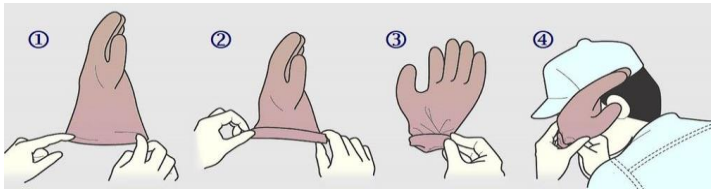
A	Protection class	**C**	Symbol: Suitable for working in live (energized) environments
B	DIN standard		

Check

All tools, equipment, protective devices and aids prescribed for safe operation and work on, with or in the vicinity of electrical installations must be suitable for this use, maintained in proper condition and used as intended.

Visually inspect protective gloves before each use for tears, cut, abrasions or other damage.

Leak test the protective gloves before each use via air entrapment and rolling up the protective glove or using a pneumatic glove tester.



Check of protective gloves

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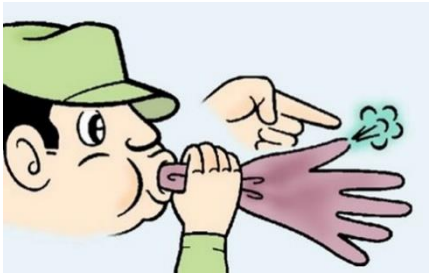

This test method may be suitable for personal equipment but due to risk of germs and contamination between individuals should not be used on any shared equipment.

Alternative check of protective gloves

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In addition, a check according to the manufacturer's specifications is necessary.

Procurement info (PPE)

According to the country-specific requirement (commercially available according to the described standards or protection scopes), personal protective equipment must be provided for the employees concerned, taking into account the respective size. Protective gloves with cotton inserts or, for hygienic reasons, with additional cotton undergloves are recommended.

Mercedes-Benz contract partners can order the personal protective equipment online via the Mercedes-Benz Partner Shop at (Source: https://partner-shop.mbvd.de).

Other markets may have a prearranged equipment ordering process such as MBUSA SSEP portal through XENTRY Workshop.

There is also the possibility to obtain PPE on the free market, just ensure all equipment meets the standards prescribed.

To this end, it should be noted that each employee must have the currently prescribed personal protective equipment. Older items that do not comply with these regulations may no longer be used.

RETESTING

Repeat tests of protective equipment and aids are necessary. The protective effect can be reduced or removed entirely by:

- Wear through use
- Weather-related influences
- Natural aging
- Change to insulating properties

All the above can reduce or completely remove the protective effect.

If externally visible damage is detected during the visual check prior to use, the protective equipment and aids must be withdrawn from further use.

The following periods are recommended for retests:

Test object	Test period	Type of test	Inspector
Insulating protective clothing (if used)	before each use	for obvious defects	User
	12 months	for compliance with the limit values specified in the electrotechnical rules	EFK
Insulating gloves	before each use	for obvious defects	User
	6 months	for compliance with the limit values specified in the electrotechnical rules	EFK
Insulated tools, cable cutters; insulating guards, actuating and grounding rods	before each use	for externally visible damage and defects	User
Voltage tester, phase comparator	before each use	for proper operation	User
Voltage testers, phase comparators and voltage testing systems (capacitive display systems) for rated voltages above 1 kV	6 months to 2 years	This depends on manufacturer, type of test equipment and environment and any applicable state laws rules	EFK

The scope and the limit values to be complied with for these tests can be found in the respective standards. After a successful retest, the protective equipment must be marked accordingly and the test must be documented.

Insulating gloves

Insulating gloves made of elastomers or plastomers according to DIN EN 60903 (VDE 0682-311) are used. They provide permanent insulation even in damp environments.

The following gloves are available for work in the low-voltage range:

- Class 00 (up to 500 V alternating voltage)
- Class 0 (up to 1000 V alternating voltage).

For higher mechanical stresses, the following options can be used:

- Thicker gloves of class 0
- Combination gloves
- Wearing protective leather gloves over the top

Insulating head protection

Insulating safety helmets must comply with DIN EN 50365 (VDE 0682-321). No periods for retests are specified for them. Since thermoplastic safety helmets are subject to natural aging, they should generally be discarded after five years at the latest.

Face protection

Face shields for electrical work can be identified by the “DIN 8” marking in accordance with DIN EN 166. They do not require retesting.

The face shield mainly protects against the possibility of an arc fault. It has been proven that commercially available face shields with a thickness of 1.5 mm can withstand even extreme arc faults.

Insulating foot protection

Insulating shoes and boots must comply with the DIN EN 50321 (VDE 0682-331) standard. This also permits steel soles. According to DIN VDE 0105-100 (VDE 0105-100), footwear with a high level of mechanical protection is not required for general use because

- Live work may only be carried out in an environment that allows safe working.
- Damp or particularly harsh environments preclude live working.

Shoes made of leather are not permitted as insulating personal protective equipment.

The insulating boots or shoes must be subjected to a retest every 12 months. The specifications of the individual testing specified in the standard are to be applied.

Body protection

When working on low-voltage overhead lines, insulating protective clothing is required to protect the body if there is a risk of “dipping in” between live parts. This clothing must meet the requirements of DIN EN 50286 (VDE 0682-301) and is suitable for rated alternating voltages up to 500 V (Class 00). In addition to a visual check, it must be subjected to a retest at the latest before one year has elapsed. This test consists of an electrical test at precisely defined points that are subject to particular stress.

In workplaces where there is an increased risk of arc flash, clothing made of flame-retardant materials, e.g. with a high cotton content, should be used.

Flexible insulating covers

Flexible covers for installations up to 1000 V alternating voltage include:

- Insulating clothes
- Insulating mats
- Insulating covers
- Stranded wire covers
- Other insulating fittings

Elastomers or plastomers are used as the material. It should be selected according to the respective application, e.g. protective effect, duration of use, sunlight.

Insulating clips are used to fix these covering materials. A visual check before each use is sufficient.

Hazards from persons not employed at the company must also be considered.

These include:

- Employees of external companies
- Employees under service and work contracts
- Visitors
- Customers

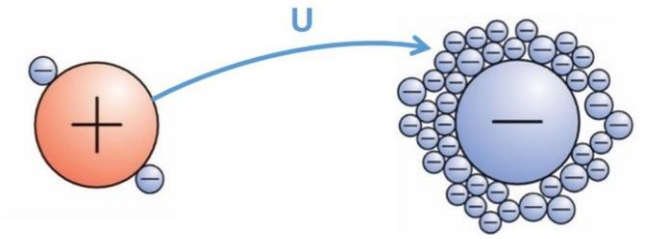
If employees of several employers work together in one workplace, their employers must coordinate in determining measures to prevent mutual hazards.

This situation could occur, for example, on construction sites, in shared offices, etc.

3 Electric Fundamentals

3.1 Electrical voltage

Electrical **voltage** is a basic physical quantity in electrical engineering. Its symbol in formulas is **U**. Its **unit of measurement** in the international system of units is the **Volt** (abbreviation: **V**).
The electric voltage is the difference of the potential electric energy, which a charge has at the two points, related to this charge. Voltage thus expresses the ability to move charges so that a current flows through the connected consumer and work is performed. A voltage occurs on a material through which current flows, which is then called a voltage drop.



Electrical voltage

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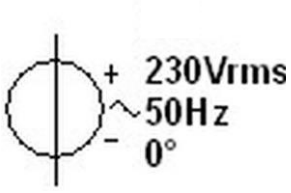
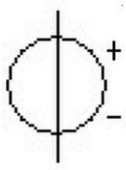
Put simply, electrical voltage can be compared to the water pressure that causes water to flow through pipes. The electrical voltage thus builds up “pressure” on the free electrons in materials, which is called the potential difference.

When is voltage considered DC Voltage?

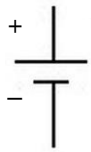
When is voltage considered AC Voltage?



Circuit symbol of an alternating voltage source

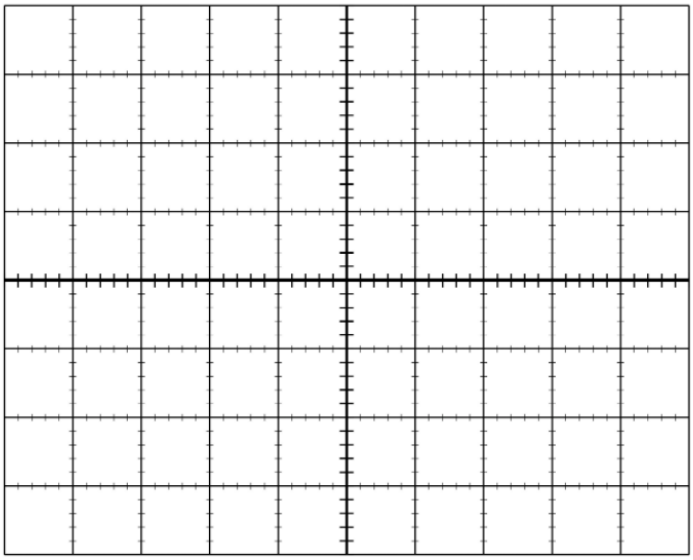


Circuit symbol of a direct voltage source

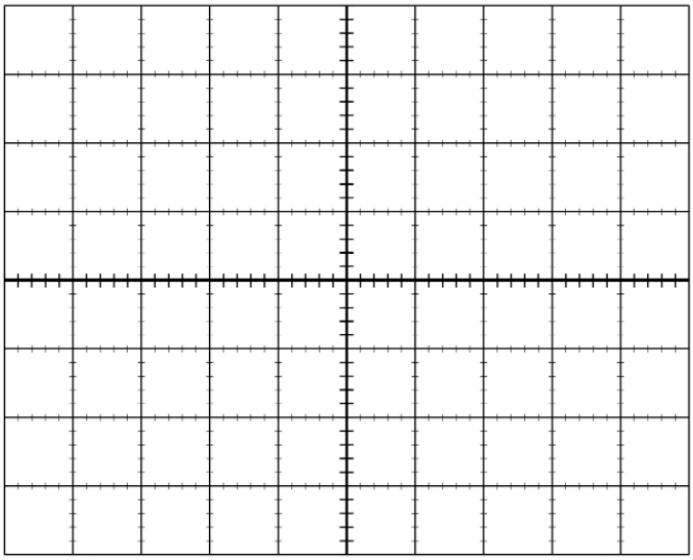


Circuit symbol of a battery cell

Draw on the graph a direct current voltage pattern that you are expecting when using an oscilloscope for a known 10 V DC power supply. Mark on your graph any reference scales on the X & Y axis.



Draw on the graph an alternating current voltage pattern that you are expecting when using an oscilloscope for a known 10 V AC power supply. Mark on your graph any reference scales on the X & Y axis.



As a refresher from the eLearnings, add the following labels to your AC pattern:

VPK **Peak Voltage Value** (aka Amplitude)

a **Period** (one complete wave cycle)

VPP **Peak to Peak Voltage** (measuring from highest peak to lowest)

The constant repetition of a period is called **frequency** (the amount of periods in 1 second)

How do you determine Root Mean Square voltage (Vrms)?
You may also know this as quadratic mean.

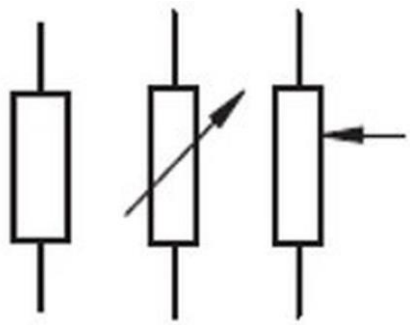
What is the V_{RMS} for an amplitude of 10 V AC?

3.2 Electrical resistance

Fundamentals

If the voltage in an electric circuit is constant, the current strength is determined by how strong the “obstruction” of the electron flow in the circuit is. By continuously increasing the voltage in a circuit, you can see that the current strength follows the voltage constantly.

The term electrical **resistance** (R) was introduced to describe this physical property of an electric circuit or an individual switching element. The symbol for electrical resistance in formulas is **R**. Its **unit of measurement** in the international system of units is the **Ohm** (abbreviation: **Ω**).



Circuit symbol of resistance

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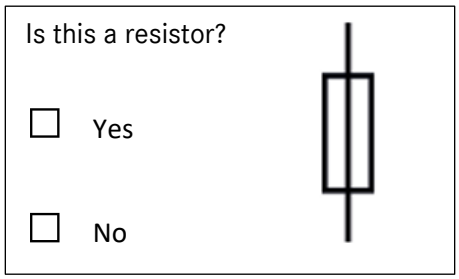
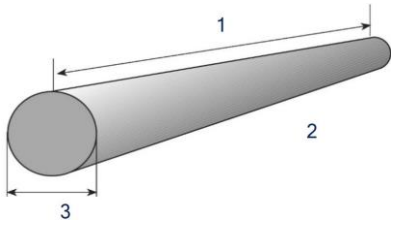


On the one hand, the electrical resistance is technically predetermined, e.g. the internal resistance of voltage sources, due to contacts and connections, on the other hand, resistors are manufactured industrially. The resistance of materials is called **specific resistance** with the formula symbol **ρ** (rho). It depends on the following factors:

Material	Specific resistance in Ω · mm²/m
Aluminum	$2.65 \cdot 10^{-2}$
Gold	$2.214 \cdot 10^{-2}$
Copper (electric cable)	$1.69 \cdot 10^{-2}$ to $1.75 \cdot 10^{-2}$
Muscle tissue	$2 \cdot 10^{6}$

Variable	Formula symbol	Unit
Specific resistance	ρ	Ω mm²/m
Length of conductor	l	m
Cross-sectional area	A	mm²

Furthermore, this material constant is temperature dependent. If the temperature of a conductor remains the same, the following relationship can be described as a formula:



Electrical conductor

$$R = \rho \cdot \frac{l}{A}$$

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1	Conductor length	**3**	Conductor diameter/cross-section
2	Conductor material		

In the case of electrical lines, the line length, the line diameter and the line material used are thus decisive for the electrical resistance.

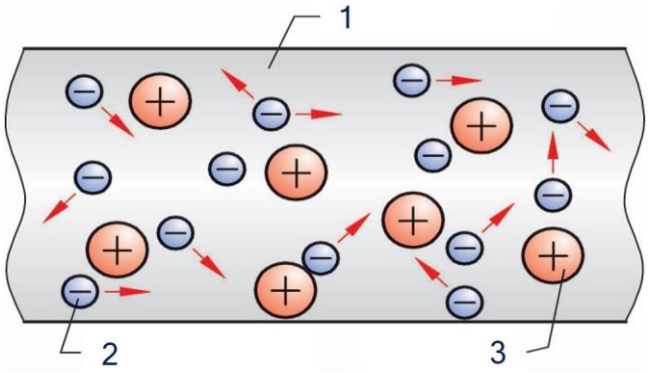
When measuring ohmic resistances, the system or component must be voltage-free.

The Ω-V socket is used as the outgoing line and the COM socket as the return line.

The measuring range selector switch is to be switched to the ohmic range.

3.3 Electric current

If no electrical voltage is applied, the free electrons move aimlessly back and forth in the material. An electric current can only flow if there are sufficient free and mobile charge carriers in a conductive material between two different electric charges. Electric current is the transfer of electrical energy and the numerical movement of free charge carriers. The flow of current can be compared to flowing water in a pipe. The more water flows through the pipe, the greater the quantity of water (flow volume). Thus, for the electric current, the more electrons that flow through the conductor in one second, the greater the electric current intensity. This is therefore used to measure the electric current numerically.



Conductor cutout

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1	Conductor cutout	**3**	Atomic core
2	“Free” electron		

Charge carriers can be electrons or ions.

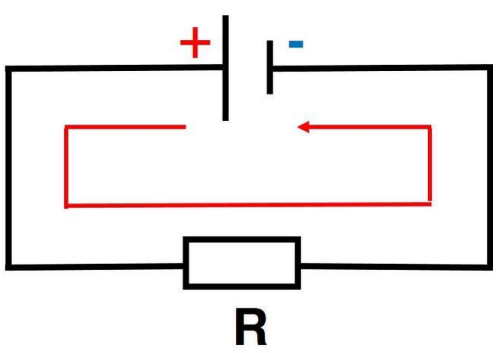
In solids, the moving charge carries are electrons that are also known as **Valence Electrons.**

In conductive liquids and gases, these are however charged atoms or molecules known as **Ions.**

The symbol for electrical **current** in formulas is **I**. Its **unit of measurement** in the international system of units (SI) is the **Ampere** (abbreviation: **A**).

Due to the history of electricity and related different scientific assumptions and findings, two current directions have been defined:

- Technical current direction (historical current direction)
- Physical current direction (direction of electron migration)



***Technical** current direction*
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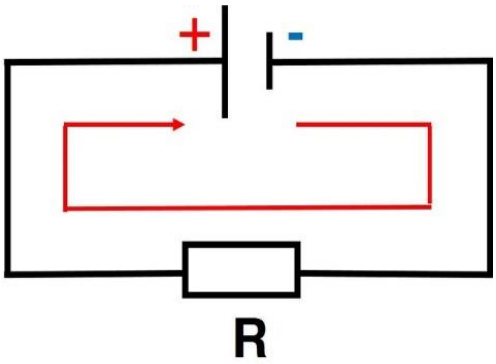

***Physical** current direction*
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The technical direction of current was defined before the structure of atoms and the relationship of electrons were known. It was assumed that positive charge carriers in metals were responsible for the flow of current. According to this view, the electrical charge carriers and thus the current should flow from the positive pole to the negative pole. Although the assumption at that time has been disproved, the original (historical/technical) direction of current has been retained for practical reasons.

For this reason, the direction of current within a circuit is still defined from positive to negative today.

When measuring amperage in a circuit it is important to place the meter in series otherwise damage to the circuit and/or the meter will occur.

3.4 Digital multimeter

In digital multimeters, the signal is recorded electronically with an analog-to-digital converter and the measured value is displayed as a numerical value.

Measuring Voltage:

When measuring voltage, they usually have a high internal resistance of 1 to 20 MΩ and their measuring ranges extend from 200 mV to 1000 V.

Measuring Current:

Current is measured by measuring the voltage drop across switchable, internal low-impedance shunt resistors. Their measuring ranges are usually between 20 µA and 20 A.

Measuring Resistance:

Resistance is measured by measuring voltage using a switchable constant power source.

The relative error limit of commercially available multimeters is usually less than one percent, depending on the measuring range.

Other measurement options:

- Acoustic continuity tester
- Frequencies
- Capacitances
- Inductances
- Transistor and diode characteristics

Further measurement options by means of built-in or external sensors:

- Humidity measurements
- Sound measurements
- Temperature measurements

Advantages of digital multimeters:

- Relatively simple, mechanical design
- Relatively inexpensive
- Operation is very simple due to the display of the units of measurement on the display
- Protective circuits against overload
- Protective circuits against polarity reversal
- Automatic selection of the voltage measuring range (auto-range function)
- Relatively insensitive to shocks and drops

Digital multimeters always require an energy supply from a battery or a power supply unit due to the internal electronics for signal processing and indication on the display.

RMS vs. TRMS

Standard multimeters calibrated for sinusoidal alternating voltages are called RMS in a frequency range up to 150 Hz. The exact values can be found in the operator's manual of the multimeter.

Multimeters calibrated for mixed voltages are called TRMS and usually have a frequency range of up to 15 kHz. The exact values can be found in the operator's manual of the multi-meter.

Root Mean Square: RMS value only for sinusoidal alternating voltages
True Root Mean Square (TRMS): RMS value for mixed voltages

Depending on the measurement task, the category of the multimeter must be selected according to CAT (category = voltage level) and the design of the measuring lines.

With unknown currents or voltages, always select the highest measurement range. Always select the correct category (CAT I to CAT IV) of the multimeter for the measuring task at hand.

Overvoltage category	In brief	Examples
CAT IV	Three-phase at utility connection, any outdoor conductors	• Refers to the "origin of installation," i.e., where low-voltage connection is made to utility power • Electricity meters, primary overcurrent protection equipment • Outside and service entrance, service drop from pole to building, run between meter and panel • Overhead line to detached building, underground line to well pump
CAT III	Three-phase distribution, including single-phase commercial lighting	• Equipment in fixed installations, such as switchgear and polyphase motors • Bus and feeder in industrial plants • Feeders and short branch circuits, distribution panel devices • Lighting systems in larger buildings • Appliance outlets with short connections to service entrance

CAT II	Single-phase receptacle connected loads	• Appliance, portable tools, and other household and similar loads
		• Outlet and long branch circuits
		  • Outlets at more than 10 meters (30 feet) from CAT III source
		  • Outlets at more that 20 meters (60 feet) from CAT IV source

CAT I	Electronic	• Protected electronic equipment • Equipment connected to (source) circuits in which measures are taken to limit transient overvoltages to an appropriately low level • Any high-voltage, low-energy source derived from a high-winding resistance transformer, such as the high-voltage section of a copier

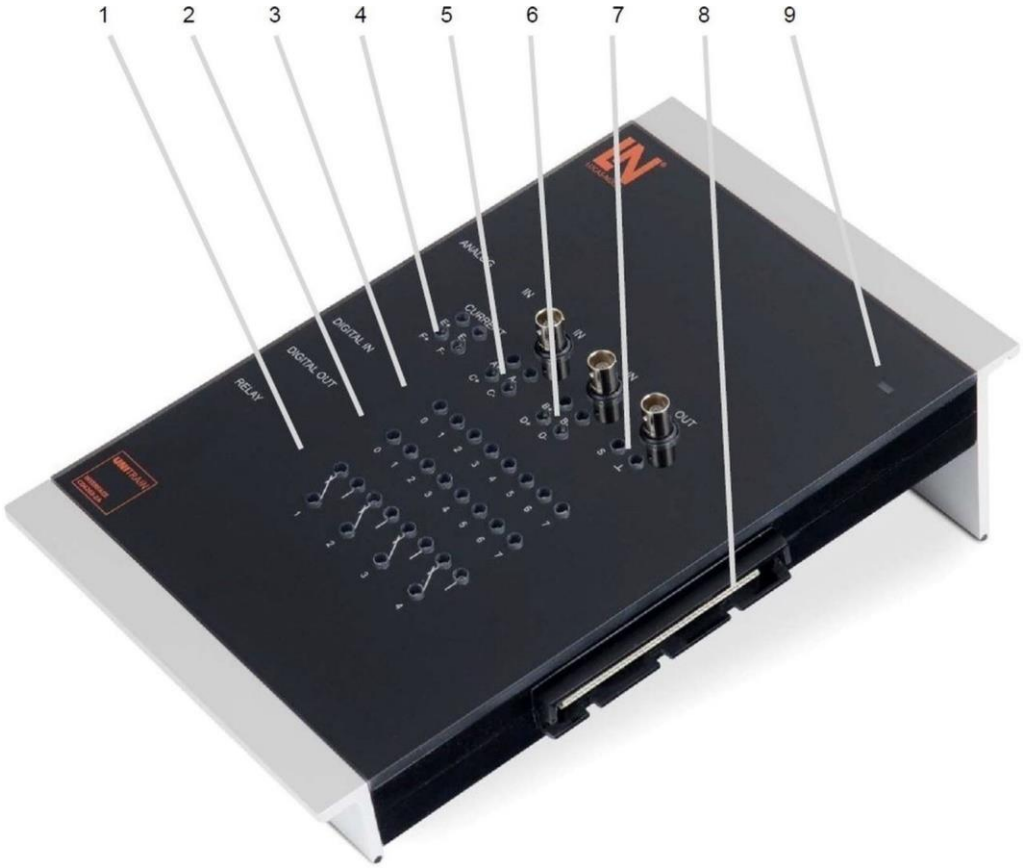
1) Which measurement range must the voltmeter be switched to if the voltage is unknown?

2) What category meter is sufficient for working on protective low voltage or extra low voltage ranges?

3.5 Presentation of Lucas-Nulle Training System

UniTrain Interface

The UniTrain interface is the central device of the UniTrain system and serves as a measuring and control interface with voltage sources and measurement inputs for laboratory work. It provides the inputs and outputs, switches, sources and measuring technology required for experimenting. The interface is controlled by the connected PC. Signals from the analog inputs and outputs are forwarded by a USB interface. With fixed voltages, the adjustable direct and alternating voltages, the variable three-phase current system and numerous virtual instruments, all sources and measuring instruments required for experimenting are available.



The UniTrain interface

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The controls and connections of the UniTrain interface are explained in the following:

1) Relay field

   Relays can be used for general switching tasks, e.g. discharging a capacitance. Of the total of eight relays, the first four are additionally routed to 2 mm sockets for experiments to be wired manually.

2) Digital outputs Q0 to Q7

   Of the total of 16 digital outputs, the first eight are additionally routed to 2-mm sockets for experiments to be wired manually. The common ground for the digital outputs is available on the Experimenter or at the analog output (7) of the interface

3) Digital inputs I0 to I7. Of the total of 16 digital inputs, the first eight are additionally connected to 2-mm sockets for experiments to be wired manually. The common ground for the digital inputs is available on the Experimenter or at the analog output of the interface (7).

4) Current measurement inputs E and F on 2 mm sockets (E+, E–, F+, F–).

5) Differential voltage inputs A and C at 2-mm sockets (A+, A–, C+, C–), input A additionally routed to BNC sockets.

6) Differential voltage inputs B and D at 2-mm sockets (B+, B–, D+, D–), input B additionally routed to BNC sockets.

7) Faster analog output at 2-mm sockets S and GND, parallel also routed to BNC sockets. The analog output is usually used as a function generator.

8) 96-pin socket connector (jack)

   Socket connector for connecting the Experimenter or an Experimenter board.

9) LED indicator lamp

   Depending on the operating status of the interface, the LED lights up in different colors. The colors have the following meanings:

   - Red: Interface starts

   - Green: Interface is connected to the computer by USB

   - Flashing red and green: Firmware update running

   - Blue: Interface connected to an existing WLAN

   - Flashing blue: WLAN mode, but not connected to the set network

   - Violet: Interface is in WLAN mode, it provides an access point for direct connection to a computer

   - Flashing blue/violet: For identifying the connected interface when establishing a WLAN connection in LabSoft

   - Orange: No connection to a computer or WLAN or there is an error

Virtual Instruments

Operation and adjustment of the hardware as well as real-time measurements during the real experiment are carried out using virtual instruments (VI), which are displayed on the PC screen. “Virtual” control elements on realistically designed laboratory equipment make it possible to work like in a “traditional” laboratory. The VIs are made available with the VI starter or the optional LabSoft software. LabSoft provides a variety of virtual instruments for real-time measurement:

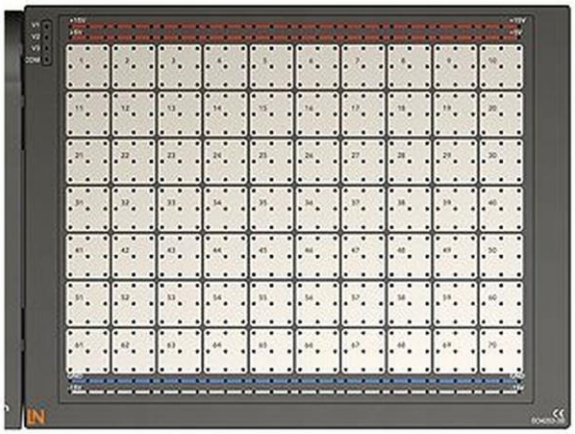
- Voltmeter, ammeter, multimeter
- Two-channel storage oscilloscope
- Function, pulse and curve form generator
- Three-phase power supply unit

UniTrain Experimenter

The UniTrain interface is intended for pairing with one or more UniTrain experimenters. The UniTrain experimenters supply additional fixed or variable experimental voltages and have an infrared interface. The UniTrain interface, the UniTrain experimenter and the experimentation cards are connected to each other by a bus (96-pin connectors). The experimenters have three alternative functionalities:

- Recording the experiment cards with prepared circuits
- Mounting the breadboard for experimenting with wired components and integrated circuits
- Docking station for multimeter (e.g. METRAHIT One Plus or LN Multi 13S) for communicating the real multimeter with the VI “multimeter”.

EloTrain Experimenter



EloTrain experimenter

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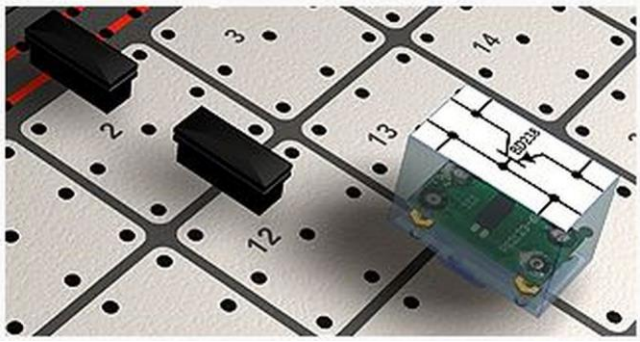
The EloTrain experimenter (plug board) for the 2-mm plug-in block system is connected to the UniTrain interface and supplied with the necessary voltages. All circuits are built on the plug-in board. It provides a secure mount for the plug-in modules and establishes a safe electrical contact of the plug-in modules to the “nodes” on the plug-in board.

70 nodes enable a clear and complex circuit setup. Each node consists of nine 2-mm sockets which are electrically conductively connected to each other. The nodes are electrically isolated from each other. The contact between individual nodes or the connection strip for the supply voltage is established in each case with a 2-mm jumper plug. Alternatively, a corresponding cable jumper can also be used.



EloTrain Experimenter – Circuit Design

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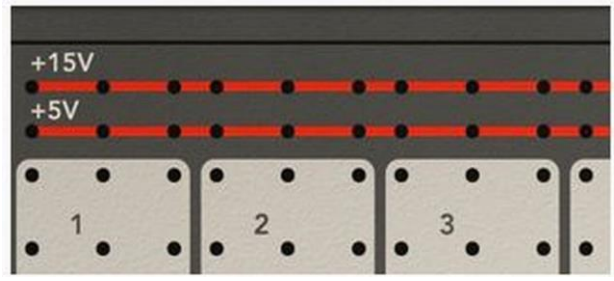
The circuit design is implemented by inserting plug-in components between the nodes. Conductive connections between the nodes are established with 2-mm/7.5-mm connectors. The connection points to the power supply are placed in such a way that the supply voltages can be made available at many points on the board with just a few jumper plugs.



EloTrain Experimenter – Power Supply

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3.6 Safety rules when handling the Lucas-Nülle training system

The Lucas Nülle training system is built according to the state of the art and the recognized safety rules. Nevertheless, improper or incorrect use may result in hazards to the life and limb of the user or third party or impairment of the training system and other material values.

The training system may only be operated in technically flawless condition and as intended, in a safety and risk-conscious manner. Malfunctions that could impair safety must be eliminated immediately.

Any person entrusted with the use, commissioning, operation, maintenance or repair of the training system must have read and understood the relevant operating instructions and, if applicable, experiment instructions. The operator's manual must be stored near the training system and must always be accessible to everyone. Valid accident prevention regulations must be kept visibly in the vicinity of the training system and accessible to everyone.

Accident-free operation

The training system is safe for operation when used properly and corresponding to the state of the art. Hazards may emanate from the training system if the:

- Training system is not operated properly.
- Training system is not used as intended.

All safety systems and operating instructions provided by the manufacturer are a prerequisite for the safe, accident-free operation of the training system. The electrical installation must comply with the relevant local standards. In particular, a suitable protective ground conductor must be provided for the training system.

The purpose of regular function checks and maintenance work is to ensure safety! The training system must be checked for externally recognizable damage and defects at the start of the exercise. Any changes that impair safety must be remedied immediately. The training personnel must ensure that the training system is always operated in perfect condition. Maintenance and cleaning work on the training system in operation is not permitted.

Existing protective devices may be removed with the energy supply switched off only during the test setup or modification and must be properly restored after completion of the work and before the system is switched on. During maintenance, cleaning or modification work on the training system, the work site must be secured in accordance with the respective conditions. The voltage must be switched off and secured against being switched on again. Components that cannot be switched off electrically must be secured against switching on by removing the fuses.

Fuses may only be removed and reinstated by personnel authorized for this purpose! Safety systems must not be modified, dismantled or disabled. Unprotected elements can cause life-threatening injuries. All safety systems such as safety shutoffs, covers and barriers must always be in working order. Operation of the training system with defective or missing safety systems is not permitted.

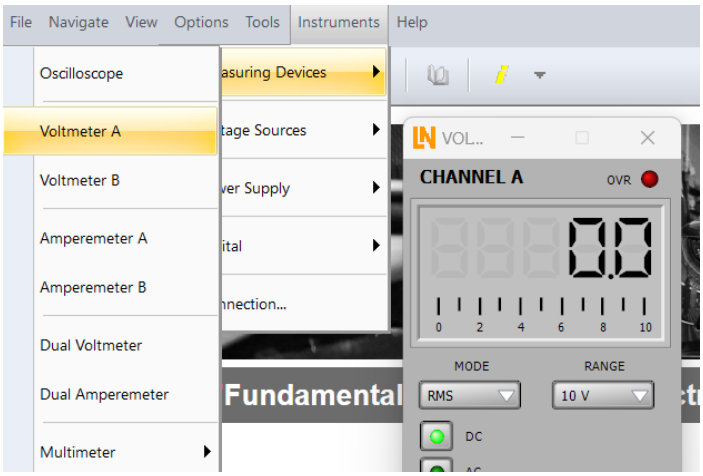
The following points must be observed before using the training system:

- Before starting the training system, check the correct function of the required safety systems.
- Persons under the influence of drugs, alcohol or medications that affect responsiveness must not operate, maintain or repair the training system.
- Only use the training system devices with the specified operating voltages!
- The training system must be grounded according to regulations! Devices with a power plug are grounded by this plug. Failure to ground the training system properly can result in life-threatening current flows!
- The devices are intended for indoor operation only.
- The interface and experimenter are designed in protection class III and are intended exclusively for operation with protective extra-low voltages.
- Do not measure voltages greater than 25 V AC or 60 V DC or currents greater than 5 A at the analog inputs!
- The 2-mm measuring cables supplied with the system may only be used within the UniTrain system (protective extra-low voltage)

3.7 Exercise 1: Measuring exercises with the Lucas-Nülle training system

A) Perform measurement exercises with the UniTrain interface and the associated software according to your trainer's instructions. For this exercise we will use the 15V and 5V power supplies on the board as well as the “Function Generator” as our voltage sources. Then use the “Voltage Meter”, “Oscilloscope” and supplied DVOM for measurements.

Open “Voltmeter A” in the Lucas Nulle software,



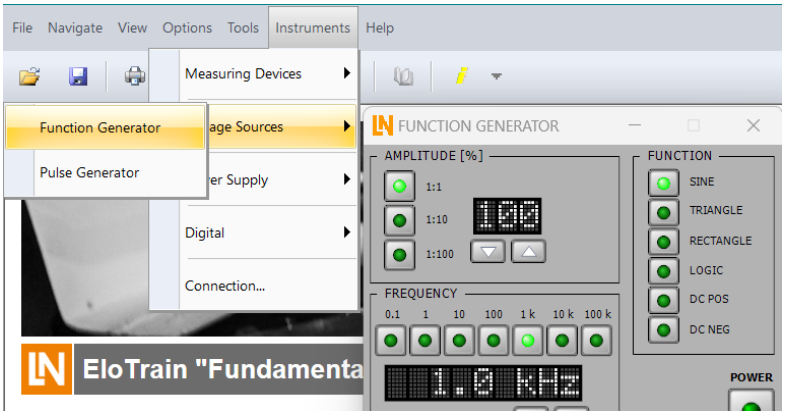
Then using the Channel A ports on the board, measure both the 15V and 5V supplies. Don’t forget to change the meter range to 20V.

Record results: _____

Repeat the measurements, this time using the DVOM.

Record results: _____

B) Now open the “Function Generator” we will now use this as our voltage source. Change the function setting to **DC POS**. This generator has a max output of 10V so with the top box being at 100% amplitude you should read 10V.

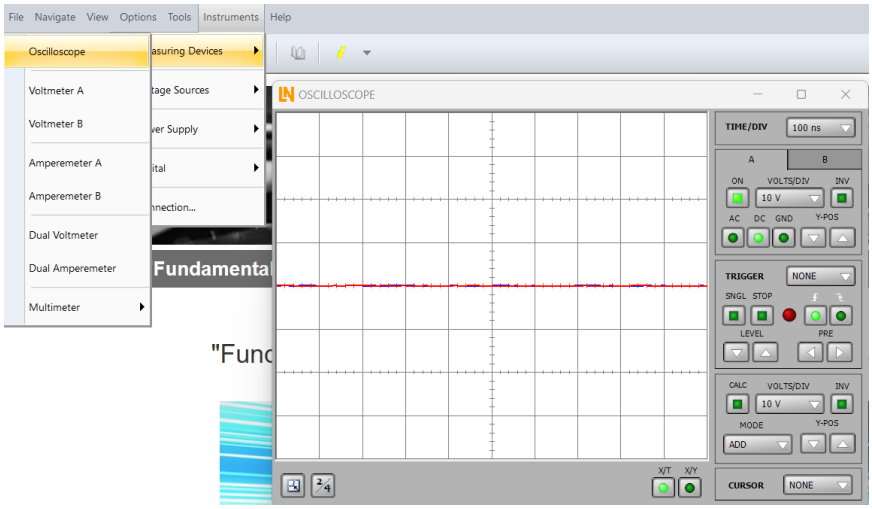


Using the same Channel A ports on the board, now plug them into the function generator ports labeled “S and ⏚”

Take a couple different measurements with the virtual voltmeter with changing the amplitude then repeat using the DVOM.

Record results: _____

C) Now open the Virtual Oscilloscope (make sure the voltmeter window is closed first), your leads should still be in the Channel A ports and the Function Generator ports.

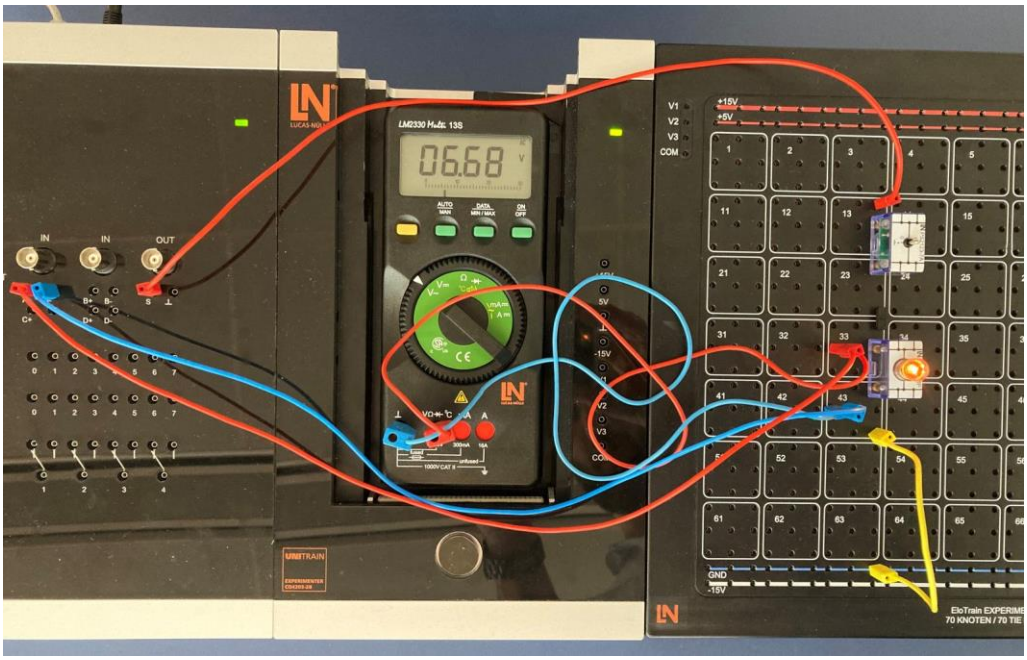


D) With the function generator set to produce 10V, now switch between the different function settings ie, Sine, Triangle, Logic to produce different wave patterns. Also try changing the frequency settings to see how that will affect your voltages/patterns.

This functions like XENTRY scope so you may have to play around with voltage and time settings until a good pattern appears on the graph.

4 Measurement of voltage

The importance of knowing which signal form applies is a crucial finding for learners. If an alternating voltage applies, measurement with an oscilloscope shall therefore be preferred.



Measurement setup – alternating voltage with multimeter

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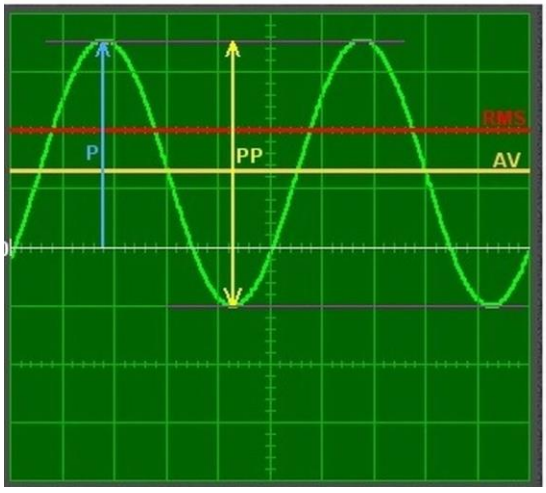
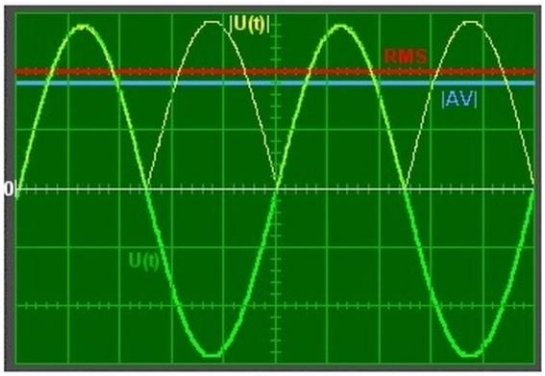
Adjustment	Measurement method
AV	Mean value
|AV|	Rectifier mean value
P	Peak value (peak value)
PP	Peak-to-peak value
RMS	Effective value (Root Mean Square)





Step 1: Select voltage type and measuring range

For voltage measurement with the multimeter, the voltage type must first be selected. Direct voltages usually apply at mobile voltage sources. Mains-operated devices usually work with alternating voltages. To do this, set the rotary switch of the multimeter to the appropriate position. The alternating voltage range is marked with a (~) and the direct voltage range with a (–). If the multimeter does not have an auto-range function, start measuring in the highest voltage range to avoid destroying the measuring device.

Step 2: Connect measuring lines and attach measuring tips

The black measuring line of the negative terminal is connected to the COM socket on the device, the red measuring line of the positive terminal is connected to the INPUT socket for voltage measurement. Now, the measuring tips can be positioned on the measuring object, for this they must always be positioned in parallel to the load or supply.

Step 3: Measure voltage

Once the measuring lines have been connected correctly and the correct measuring range has been set, the multimeter is ready for measurement. To operate the multimeter, the device must be started up using the on/off switch. Many multimeters switch on automatically when the required measuring range is selected. The voltage in volts can now be read directly on the multimeter display.

After the measurement has been completed, the switch must be returned to the “OFF” position. In some measuring devices, an automatic shutoff takes place after a defined time to protect the internal battery.

Notes on voltage measurement with the multimeter

- Before measuring, read the operator’s manual of the multimeter carefully.
- For voltage measurement, the multimeter is connected in parallel to the voltage source or the object to be measured. In order to avoid excessive current flow through the measuring device and thereby possibly falsifying the measurement result, there is a very high internal resistance for voltage measurement.
- Select direct voltage or alternating voltage.
- For alternating voltage measurement, the RMS value is displayed.
- The polarity of the measuring cables is important for direct voltage measurement. When swapping the measuring tips, the pointer of an analog measuring device would swing in the wrong direction. A digital multimeter would display a negative measurement value.
- In the case of unknown measurement values, the highest measuring range is always selected.
- Use secure measuring cables with suitable measuring tips.
- Use full batteries in the device to avoid measuring errors.
- After use, switch off the device or set it to the largest measuring range.

Components of an elementary electric circuit

Answer the following questions and discuss the solutions with the trainer with the whole group.

a) Which components make up an elementary electric circuit?

b) Draw an elementary electric circuit. Note that an electrical engineering drawing must always be drawn when switched off.

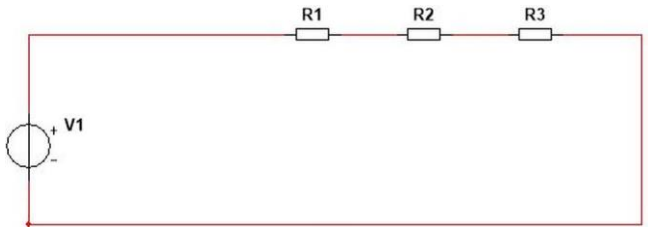
c) Which properties of the circuit effect current levels?

d) How can the consumer resistance effect the circuit current and its components?

4.1 Series and parallel circuit

When using multiple voltage sources or consumers, series or parallel circuits are created depending on their arrangement.

Series Circuit



Series circuit

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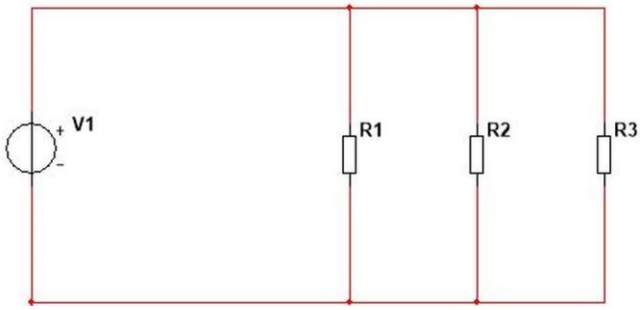
If all components are connected one after the other without branching off, this is called a series circuit. The **same current flows through all components**. The total voltage is divided between the individual components.

Parallel Circuit



Parallel circuit

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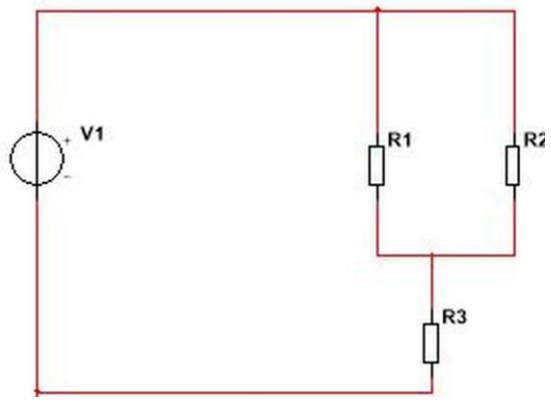
If components are connected in parallel, several paths are created for the current. These paths are called current branches. The same voltage is present at parallel consumers. The **total current is divided** among the individual current branches.

Mixed Circuit (Series-Parallel):



Mixed circuit

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Circuits that contain elements of both series circuits and parallel circuits are called mixed circuits. Every mixed circuit can be traced back to series and parallel circuits. The laws of these circuits are described by Kirchhoff's rules.

With the following given values, determine what the total resistance of each of the 3 above circuits would be.

R1 = 50Ω R2 = 100Ω R3 = 200Ω

Series Circuit - _____

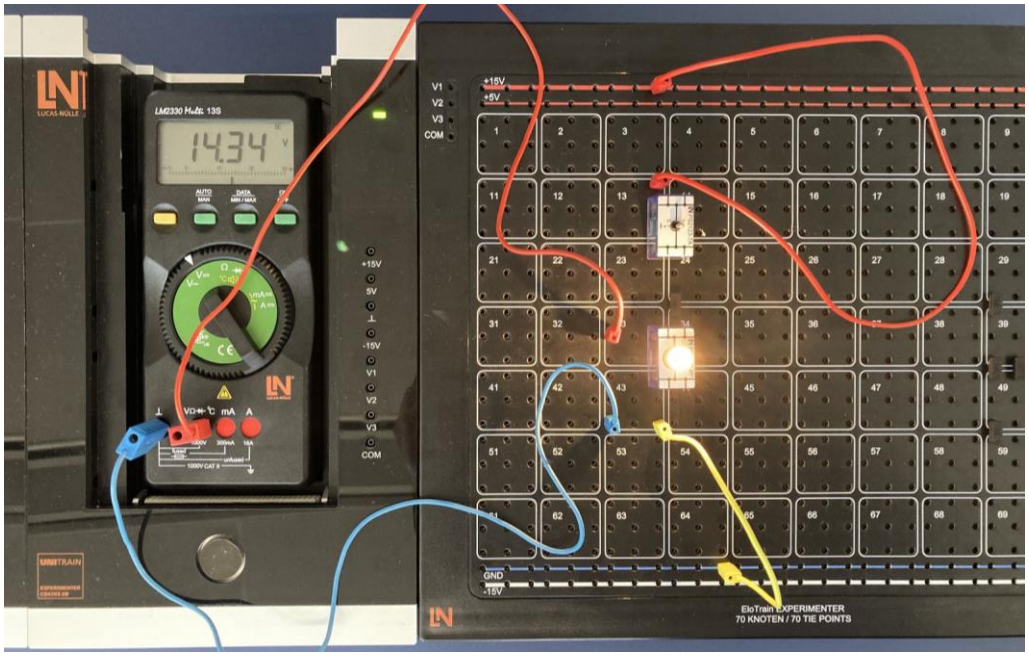
Parallel Circuit - _____

Mixed Circuit - _____

4.2 Exercise 2: Voltage measurement using multimeter

With support from your trainer, set up the simple circuit just discussed in the training system. Use the installed 15-V power supply of the connector board. Use the following components for this purpose:

- Training system (UniTrain interface and experimenter, EloTrain experimenter)
- Multimeter
- PS2123-8P bulb
- PS2123-7A switch
- Power supply U = 15 V DC



a) Once the trainer has approved the circuit, you can switch the bulb on and off at the switch.

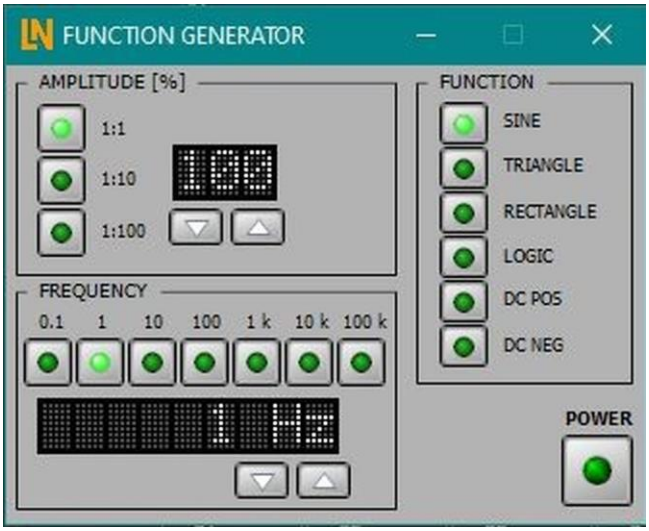
Now measure the voltage at the consumer. Observe the measurement value in switch position “0”. Then switch to switch position “1”. What is the measured voltage?

b) Now swap the measuring cables and once again measure the voltage. What is the measured voltage? Which effect does the exchange of the measuring cable have?

c) Now measure the voltage that drops when it passes through the switch. Take another look at the measured value in switch position “0” and then in switch position “1”.

Measurement of alternating voltage with the multimeter

Replace the installed DC power supply of the connector board with the virtual function generator of the UniTrain interface. Set a sinusoidal AC voltage with the settings shown below.



Settings in the function generator

GTT_013641

a) Now use the multimeter to measure the voltage that drops when it passes through the consumer. What do you notice?

b) Gradually increase the frequency of the alternating voltage to 100 kHz. How does the measured value change?

f = 10 Hz	
f = 50 Hz	
f = 100 Hz	
f = 1 kHz	
f = 10 kHz	
f = 100 kHz	

c) In the next step, measure the voltage using the “virtual voltmeter A”. What are the effects of the different display settings?

AV	
|AV|	
P	
PP	
RMS	

d) What does the designation “effective value mean”?

e) Replace the bulb with a resistor R = 1 MΩ. Now measure the effective value of the alternating voltage (f = 100 Hz) simultaneously with the multimeter 13S and with the virtual voltmeter. Measure for the following voltage types: “Sinusoidal voltage” (SINE), “triangular voltage” (TRIANGLE) and “rectangular voltage” (RECTANGLE). What do you observe? Which statements can be made on the basis of readings from the measuring devices?

Voltage type	**U_{eff} - M13S**	**U_{eff} – VI**
Sine		
Triangle		
Rectangle		

4.3 Exercise 3: Voltage measurement using oscilloscope

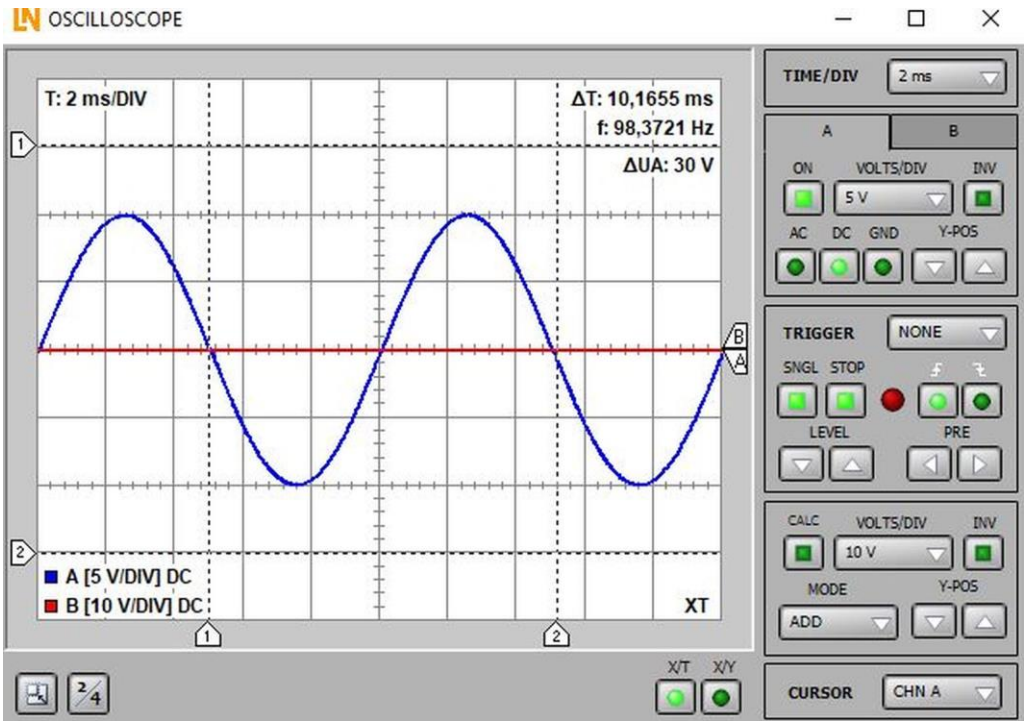
An oscilloscope can be used to display or measure the voltage and cycle duration of a signal. The voltage and the cycle duration can be read directly from the screen. The frequency of a recurring signal can be calculated from the cycle duration.

Measurement of direct (DC) or alternating voltage (AC)

- To measure a voltage, it is applied between the input channel and the ground socket. The rotary knob for the measuring range must be adjusted so that the signal is deflected as far as possible in vertical direction. The zero line can be set with the Y-position controllers when the switch for AC, DC and GND is in the GND position. When measuring an alternating voltage, the measured voltage represents the peak/peak value of the alternating voltage (UPP).

Measuring the cycle duration T

- To do so, the cycle duration must first be defined. A period of a regularly repeating signal is over when the signal has reached the output amplitude again. The cycle duration T results from the set scale of the x-axis (s/DIV) multiplied by the number of display fields of a period.



Cycle duration

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Measurement of alternating voltage with the oscilloscope

Keep the circuit from the previous task. Create alternating voltage with the virtual oscilloscope. Change the following values:

- Voltage type
- Alternating voltage frequency
- Amplitude height

Use the cursor function to determine the amplitude and frequency of the displayed signal

Once you establish peak voltage, use the formula to calculate RMS Voltage. Then prove with multimeter.

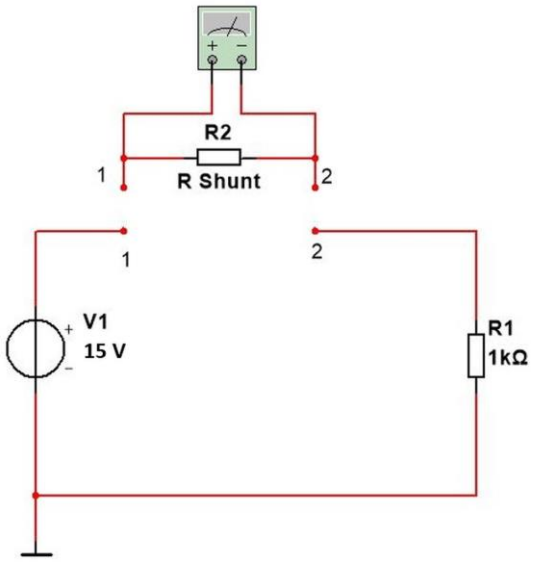
For your notes:

4.4 Indirect current measurement using a shunt

The term shunt was originally used for an electrically conductive component that is connected parallel to the electric circuit and has the task of diverting an electrical current from a circuit part. Today, the term shunt typically refers to a low-ohm measuring resistor that is inserted directly into the live cable.

With indirect current measurement, the current in the circuit is not determined with an ammeter, but using shunts and a voltmeter. The advantage of indirect current measurement is the graphical and metrological representation of a current by a voltage measurement. At an ohmic resistor, current and voltage are always “in phase”, which is why the voltage-time function is the same as the current-time function and can therefore be illustrated on the oscilloscope. Current measurement using a shunt is particularly used when the current to be measured exceeds the unit of the measuring device.

The structure of a circuit for indirect current measurement is shown in the figure below. The measurement object here is resistor R_1. The shunt is connected to the electric circuit via items 1 and 2 and is shown separately for reasons of clarity.



Indirect current measurement – schematic diagram

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According to the Kirchhoff's second law, the same current flows through all components in a series circuit. This results in the relationship:

$$I = \frac{U_{Shunt}}{R_{Shunt}}$$

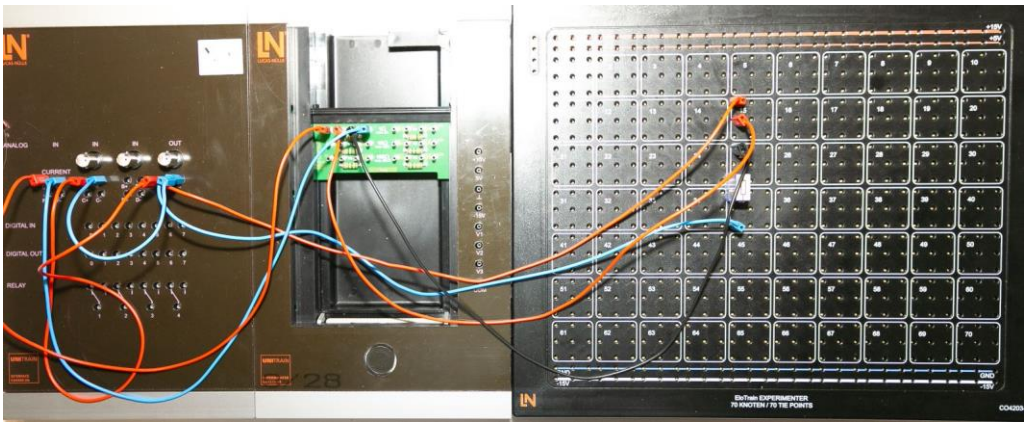
A disadvantage of indirect current measurement is that the precision resistor, which is additionally integrated into the circuit, influences the current to be measured. This happens after the relationship:

$$I = \frac{U}{R_1 + R_{Shunt}}$$

From this relationship it follows that the shunt resistance must be much smaller than the measurement resistance. For the circuit shown above, the following shall apply: $R_{(Shunt)} \leq R_{(1)}$. The resulting measuring error will be less than 1% under this prerequisite

4.5 Exercise 4: Indirect current measurement with shunt

Rebuild the circuit for indirect measurement of current I_1 through resistor R_1 on your connector board. The external shunt printed circuit board is used for this test.



Circuit design for indirect current measurement

GTT_010326

Use the following components for this purpose:

- Training system
- Multimeter 13S
- Resistance R_1 = 1 kΩ
- Power supply U = 15 V
- Shunts: 1 Ω, 10 Ω, 100 Ω

Integrate the individual shunt resistors R_{Shunt1} = 1 Ω, R_{Shunt2} = 10 Ω, R_{Shunt3} = 100 Ω according to the circuit diagram one after the other. To do this, connect the measuring cables of the virtual voltmeter to the respective shunt resistor.

R_{Shunt}	1 Ω	10 Ω	100 Ω
$U_{Shunt\ Measurement}$			
$I_{calculated}$			
$I_{measurement}$			

a) The control unit will monitor the voltage drop of the SHUNT resistor and use this value to calculate amperage. This is called an INDIRECT measurement. To show how this is done first we need to measure the voltage drop across the shunt resistors. Set meter to measure mV to get the most accurate results. Enter the values into the chart.

b) With the voltage drop of each shunt resistor, you can now calculate the amperage by using the resistance value of the shunt (voltage drop of shunt 1 ÷ resistance of shunt 1). This is how the control unit or monitor would read current in the circuit.

c) Now to prove youre calculations, use your DVOM, or the dual amperemeter function on the computer, to take a current measurement of the circuit with each of the shunt resistors wired in series with the circuit resistor R1. Enter the values into the chart.

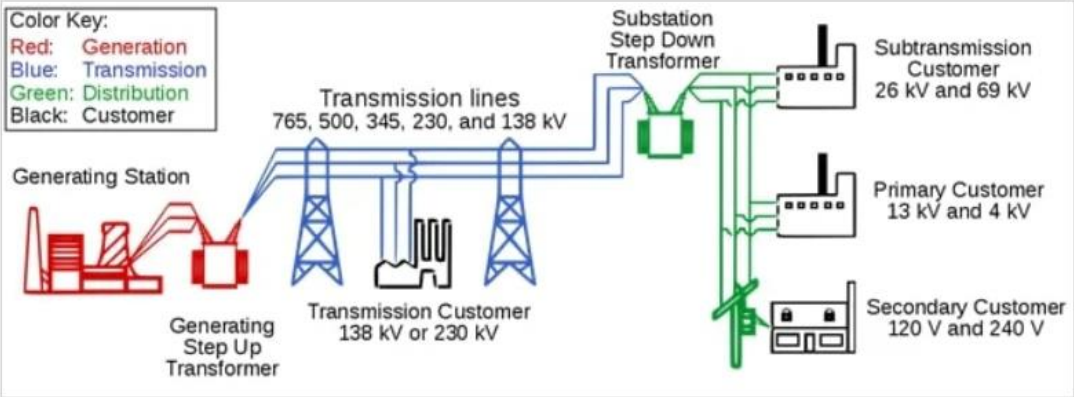
4.6 Exercise 5: Indirect current measurement using oscilloscope

Keep the previous circuit for indirect current measurement. Instead of the 15-V power supply of the connector board, use the virtual function generator. Create an alternating voltage with an amplitude of 10 V and a frequency of f = 100 Hz.

Illustrate the voltage curve through the shunt resistor of 10 Ω using the virtual oscilloscope. Determine the amplitude and effective value of the alternating current. Then use these values to determine current in the circuit.

5 High-Voltage Infrastructure / Electrical Networks

5.1 Overview of Electrical Networks



Electricity from the powerplants is distributed around the country to sub-stations, where it is transformed into various voltages for household, businesses, industrial sites, charging stations and much more.

The voltages that are used to distribute electricity in USA are generally between 230 – 500 kV, when these voltages enter the local transformers, the voltages are dropped as required and may be distributed at lower voltages and then additionally reduced closer to the consumer.

There are various standards / regulations that ensure safe power supply is assured. This usually takes the form of the different grounding system or sometimes known as earthing system.

These standards / regulations can vary from country to country as well as final application but generally follow similar standards. Due to these variations, there is a 2 to 4 letter acronym used to identify the variations.

Generally applicable to all networks	
1st letter: Description of the grounding situation of the voltage source	
T	Direct grounding of one point via the system ground, usually the star point of the transformer
I	Active parts are isolated from ground
2nd letter: Grounding conditions at the bodies of the electrical system	
T	Direct grounding of equipment bodies
N	Direct connection of the bodies of equipment with the grounded star point of the supply network
3rd letter: Description of the location of PE and neutral conductors	
C	Neutral conductor and protective earth conductor combined into PEN conductor
S	Neutral conductor and protective earth conductor separate

An earthing system (UK and IEC) or grounding system (US) connects specific parts of an electric power system with the ground, typically the Earth's conductive surface, for safety and functional purposes.

The choice of earthing system can affect the safety and electromagnetic compatibility of the installation. Regulations for earthing systems vary among countries, though most follow the recommendations of the International Electrotechnical Commission (IEC).

5.2 TN Network

In a TN earthing system, one of the points in the generator or transformer is connected with earth, usually the star point in a three-phase system. The body of the electrical device is connected with earth via this earth connection at the transformer.

The conductor that connects the exposed metallic parts of the consumer's electrical installation is called protective earth (PE; see also: Ground). The conductor that connects to the star point in a three-phase system, or that carries the return current in a single-phase system, is called neutral (N).

Three variants of TN systems are distinguished:

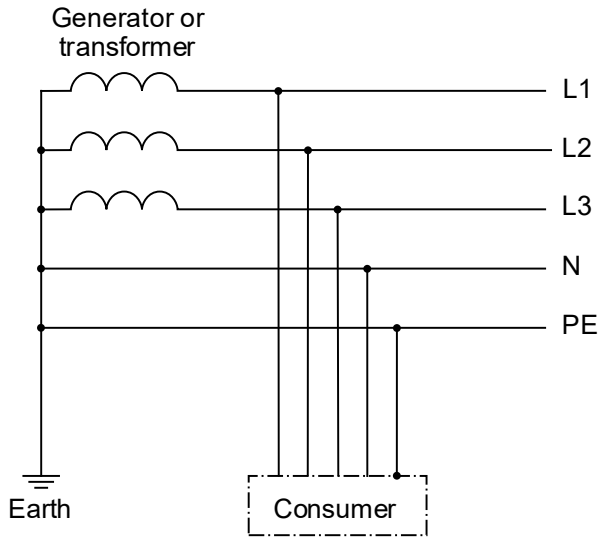
TNS

TNC

TNCS

TN-S:

PE and N are separate conductors that are connected together only near the power source.



T - Terra

The energy source is grounded.

N -The consumer has one neutral conductor

Asymmetric consumers conduct the current via the neutral conductor back to the energy source. The neutral conductor is usually blue. However, it may have other colors and numbers.

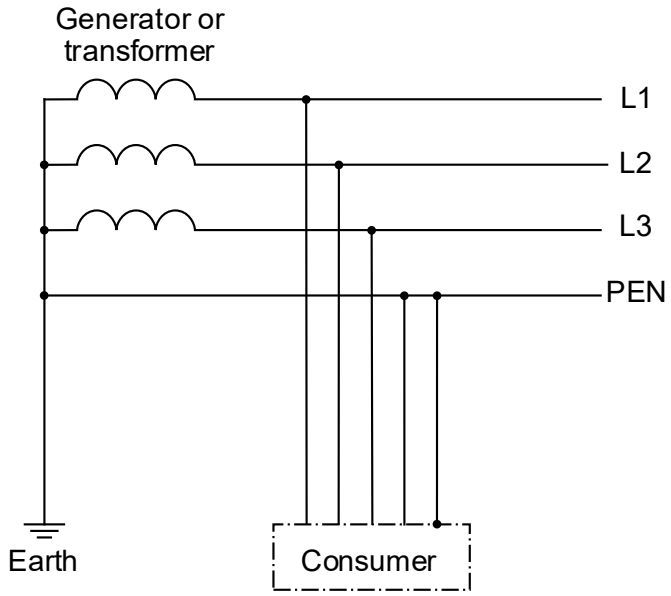
S - Separate

The separate conductor may only be green/yellow. The conductor has a purely protective function. The conductor may only carry current in case of a fault or for testing purposes.

In a TN-S network, there is an additional protective ground conductor in addition to the supply and return lines.

TN-C:

A combined PEN conductor fulfills the functions of both a PE and an N conductor. (on 230/400 V systems normally only used for distribution networks)



T - Terra

The energy source is grounded.

N -The consumer has one neutral conductor

Asymmetric consumers conduct the current via the neutral conductor back to the energy source. The neutral conductor is usually blue. However, it may have other colors and numbers.

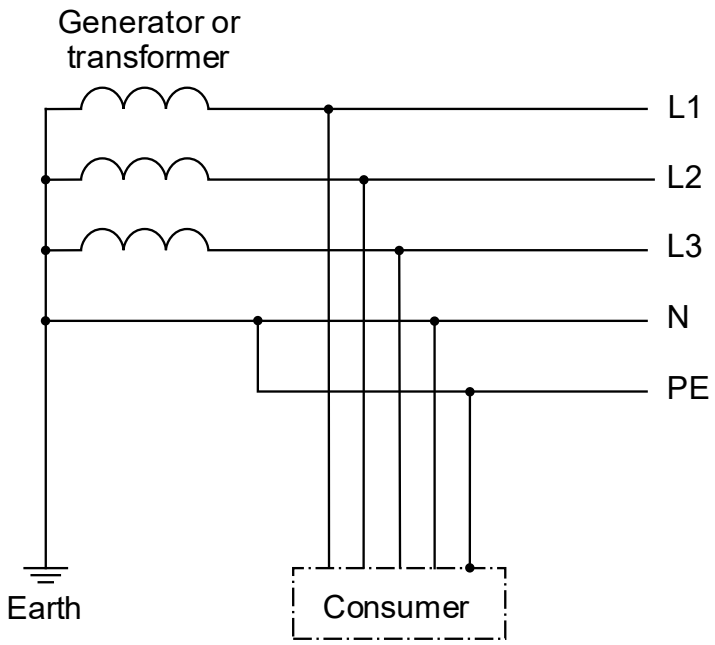
C - Combined

The neutral conductor and ground are combined on one line.

Some older homes, especially those built before the invention of residual-current circuit breakers and wired home area networks, use an in-house TN-C arrangement. This is no longer recommended practice.

TN-C-S:

Part of the system uses a combined PEN conductor, which is at some point split up into separate PE and N lines. The combined PEN conductor typically occurs between the substation and the entry point into the building, and earth and neutral are separated in the service head.



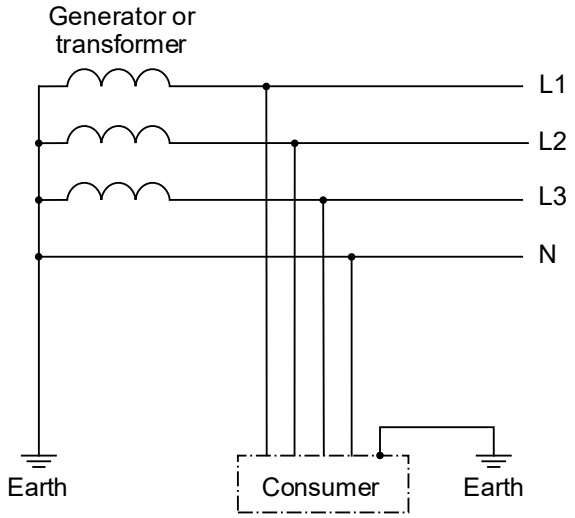
In the United States National Electrical Code and Canadian Electrical Code, the feed from the distribution transformer uses a combined neutral and grounding conductor, but within the structure separate neutral and protective earth conductors are used (TN-C-S). The neutral must be connected to earth only on the supply side of the customer's disconnecting switch.

Newer residential areas in Europe are mostly built with TN-C-S, in a large degree driven by the fact that three-phase products for the consumer market - such as electric vehicle charging stations - are developed for the European market where TN systems with 400V between the phases dominate.

As most countries have adopted the TN-C or TN-S or TN-C-S network, when connecting the vehicles charging cable, the AC charger of the vehicle is usually connected to the TN-S network.

5.3 TT Network

In a TT earthing system, the protective earth connection for the consumer is provided by a local earth electrode, and there is another independently installed at the generator. There is no 'earth wire' between the two. The fault loop impedance is higher, and unless the electrode impedance is very low so a TT installation should always have an RCD as its first isolator.



First T - Energy source is grounded

Second T - Consumers are grounded locally

TT systems are known to be used in quarries.

Some energy suppliers still operate TT systems in construction engineering.

Provided that the local ground is routed to a potential equalization rail, a TT system can be considered to be the same as a TN system.

The safety shutoff times are different when compared to a TN system:

TT network: U = 230V, ta = 0.2 seconds

TN network: U = 230V, ta = 0.4 seconds

However, since the grounding electrode resistance is subject to severe fluctuations depending on weather conditions, it is often extremely difficult to adhere to the shutoff conditions in a TT network. For this reason, most energy suppliers prescribe a ground fault circuit interrupter (GFCI) as additional protection.

The big advantage of the TT earthing system is the reduced conducted interference from other users' connected equipment.

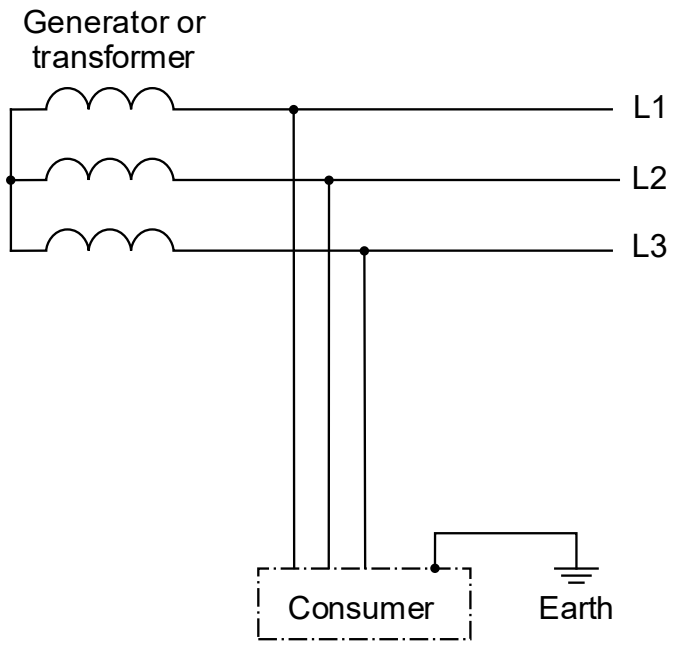
TT networks do not pose any serious risks in the case of a broken neutral. In addition, in locations where power is distributed overhead, earth conductors are not at risk of becoming live should any overhead distribution conductor be fractured by, say, a fallen tree or branch.

In pre-RCD (Residual Current Devices) era, the TT earthing system was unattractive for general use because of the difficulty of arranging reliable automatic disconnection (ADS) in the case of a line-to-PE short circuit (in comparison with TN systems, where the same breaker or fuse will operate for either L-N or L-PE faults). With RCD technology now mitigating this disadvantage the TT earthing system has become more attractive providing all AC power circuits are RCD protected.

The TT earthing system is used throughout Japan, with RCD units in most industrial settings or even at home. This can impose added requirements on variable frequency drives and switched-mode power supplies which often have substantial filters passing high frequency noise to the ground conductor.

5.4 IT Network

In an IT network (isolé-terre), the electrical distribution system has no connection to earth at all, or it has only a very high-impedance connection.



I - Isolated The energy source is isolated to ground

T - Terra Consumers grounded

Continuous insulation monitoring takes place.

Shut off only on the second isolation fault.

Applications of IT networks:

- Hospitals
- Mining
- Shipbuilding
- Electric mobility

In IT systems, a single insulation fault is unlikely to cause dangerous currents to flow through a human body in contact with earth, because no low-impedance circuit exists for such a current to flow.

However, a first insulation fault can effectively turn an IT system into a TN system, and then a second insulation fault can lead to dangerous body currents. Worse, in a multi-phase system, if one of the line conductors made contact with earth, it would cause the other phase cores to rise to the phase-phase voltage relative to earth rather than the phase-neutral voltage.

IT systems also experience larger transient overvoltage's than other systems.

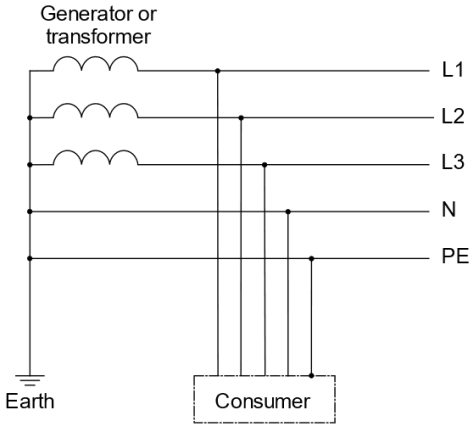
Since there is no protective ground conductor with a corresponding residual current circuit breaker (RCD) in an IT system, the insulation resistance is permanently monitored.

As our vehicles follow an IT architecture, the design and isolation of the high-voltage system from the 12 V on-board electrical system is specified in ECE R 100.

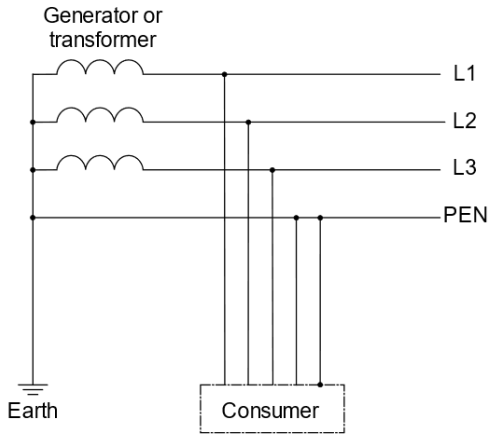
5.5 Comparison

	TT	IT	TN-S	TN-C	TN-C-S
Earth fault loop impedance	High	Highest	Low	Low	Low
RCD preferred?	Yes	Yes	Optional	No	Optional
Need earth electrode at site?	Yes	Yes	No	No	Optional
PE conductor cost	Low	Low	Highest	Least	High
Risk of broken PEN-conductor	No	No	High	Highest	High
Safety	Safe	Less Safe	Safest	Least Safe	Safe
Electromagnetic interference	Least	Least	Low	High	Low
Safety risks	High loop impedance (step voltages)	Double fault, overvoltage	Broken PE	Broken PEN	Broken PEN
Advantages	Safe and reliable	Continuity of operation, cost	Safest	Cost	Safety and cost

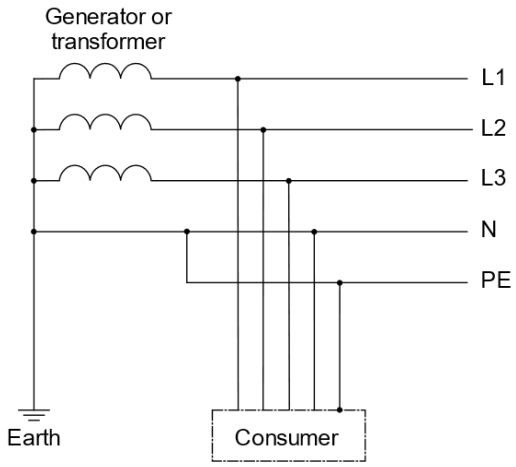
Source: https://en.wikipedia.org/wiki/Earthing_system



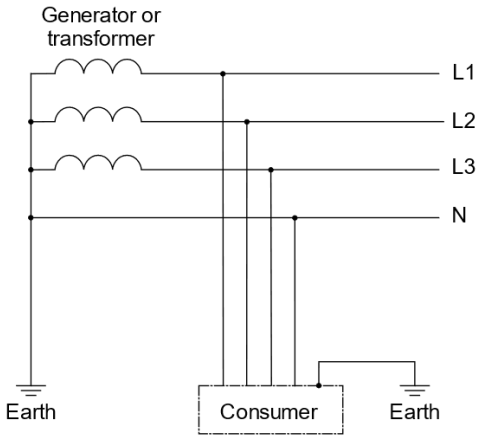
TN-S



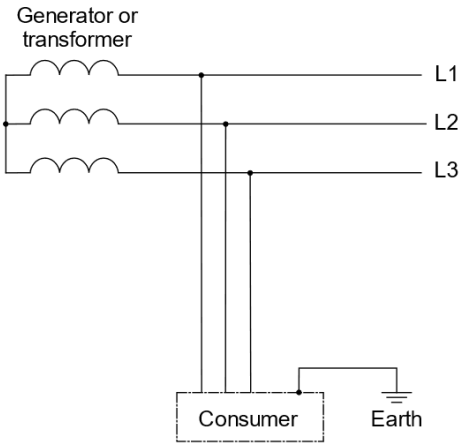
TN-C



TN-C-S



TT



IT

6 Day 1 Review

When is electrical voltage referred to as an alternating voltage?

What are the five safety rules, and when should they be applied?

When working on electrical systems what conditions can cause harm to humans?

What effect can an Alternating Current of > 30V have on the human body?

What effect can a Direct Current of > 60V have on the human body?

What checks must an employee perform before commissioning an electric device?

What dangers can arise from electrical energy?

What potential hazard or risk requires PPE?

How should you connect the meter when taking Current measurements? Voltage?

What CAT rating meter is needed for low and extra low voltage range?

What are the moving charge carriers in Solids called? Gases?

Which electrical network does the high voltage on board electrical system use?

Which factors primarily influence the ohmic resistance of a conductor?

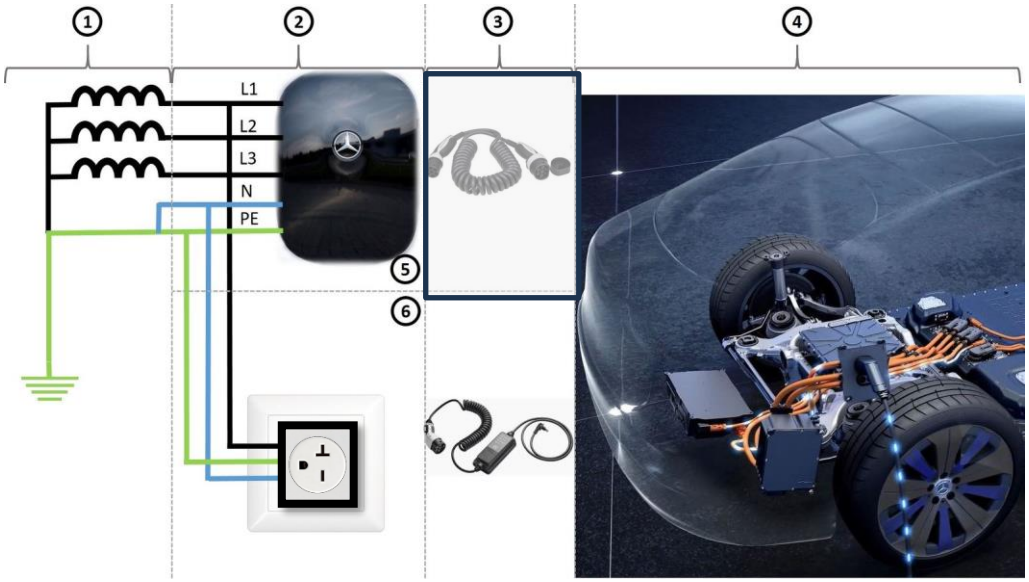
7 Current Faults

7.1 AC circuit in high-voltage vehicle

Various protective methods are used in a high-voltage vehicle to avoid fault currents. The distinctions refer to high-voltage DC and high-voltage AC circuits.

The high-voltage on-board electrical system comprises various components. When connecting to a charging device, e.g. a wallbox, the high-voltage on-board electrical system is extended. The power supply equipment and the vehicle are connected.

It is therefore important to know the associated special features. Components, such as the high-voltage charging cable and the vehicle-side charging socket establish a connection to the corresponding infrastructure during charging. It is therefore just as important to know where the boundaries between vehicle and infrastructure are. This is the only way to ensure safe work on high-voltage vehicles.

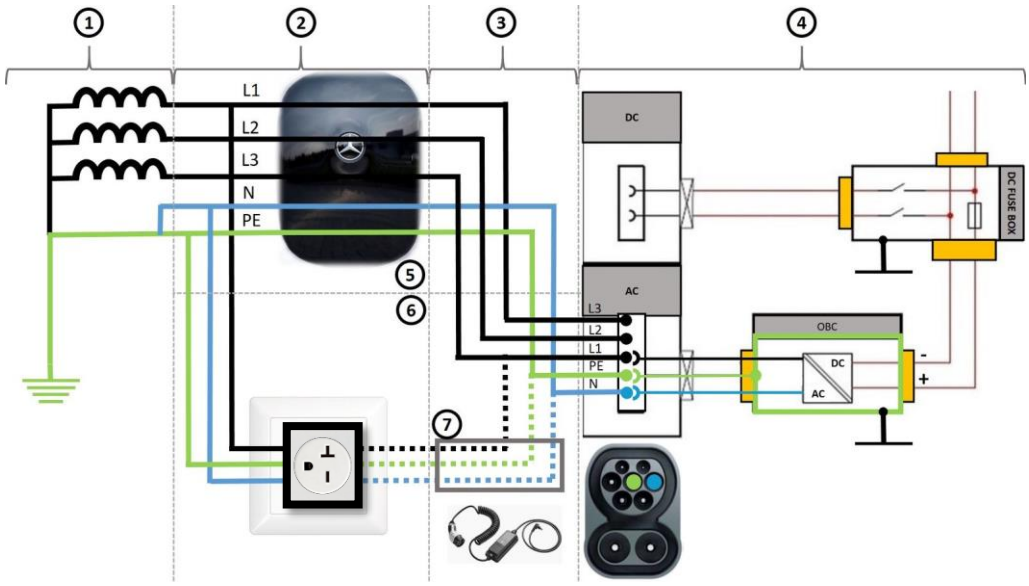


Infrastructure

GTT_013668

1	Energy source	**4**	Vehicle
2	Domestic connection	**5**	Wallbox charging station
3	Charging cable	**6**	Protective contact socket

Where is the protection if a fault occurs between the charge socket and the on-board charger?



High-voltage vehicle and infrastructure

GTT_013669

1	Energy source	**5**	Wallbox charging station
2	Domestic connection	**6**	Protective contact socket
3	Charging cable	**7**	Mode 2 charging cable with In-Cable Control Box (ICCB)
4	Vehicle		

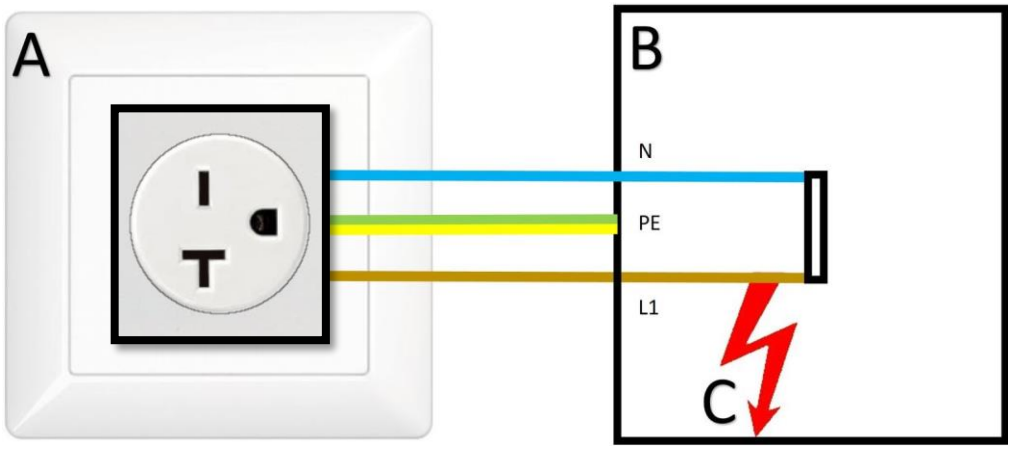
7.2 Current Fault Types

Fault current types are defined terms that describe various fault profiles in electrics. Their effects are different and depend on the system used (e.g. participant network or IT network).

Fault to frame

Fault to frame describes an unwanted, electrically conductive connection between a live cable and the housing of a consumer, e.g.

- a connection of HV+ to the housing in the power electronics or
- a connection of L1 to the housing in a toaster.



Fault to frame

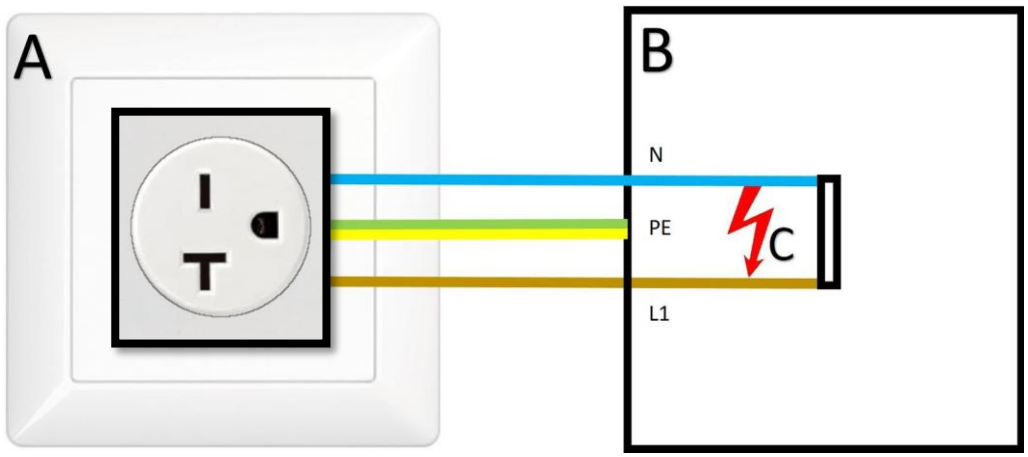
GTT_013671

A	Socket	**C**	Conductive connection between L1 and the housing
B	Consumer		

Short circuit

A short circuit describes an unintended low-ohmical connection between two different potentials, e.g.

- connection from HV+ to HV- or
- connection from L1 to N.



Short circuit

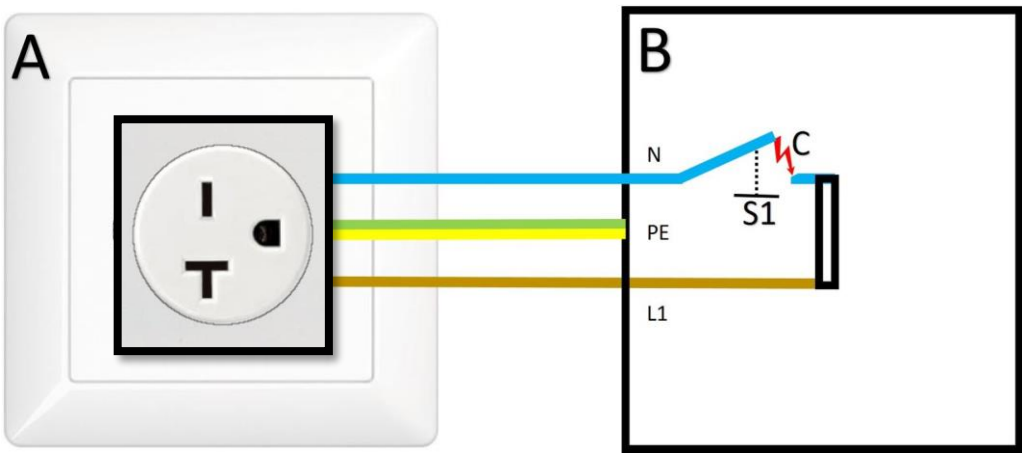
GTT_013670

A	Socket	**C**	Low-ohmic connection between L1 and N
B	Consumer		

Conductor short

The conductor short describes an unintended, electrically conductive connection of two similar potentials, e.g.

- jumper in an open switch or
- connection from one positive cable to another positive cable.



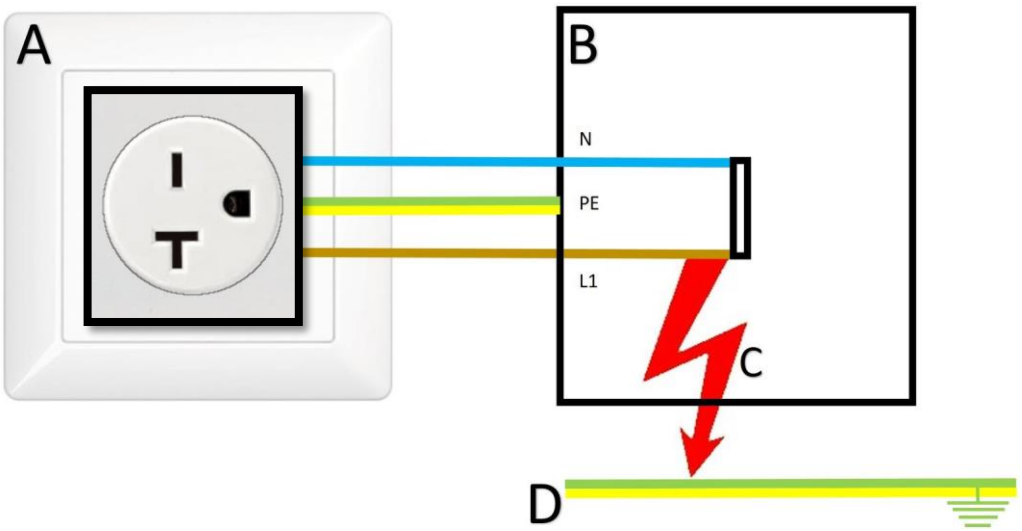
Conductor short

GTT_013673

A	Socket	**C**	Conductive connection in an open switch
B	Consumer		

Ground fault

The ground fault describes an unwanted, electrically conductive connection of a live cable to ground, e.g. a connection between L1 and the ground potential.

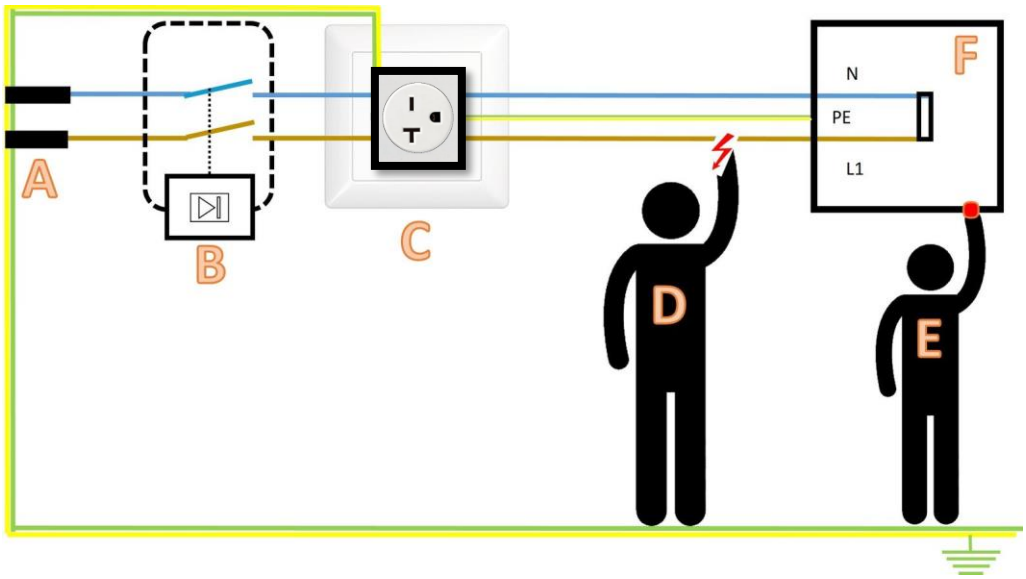


Ground fault

GTT_013672

A	Socket	**C**	Conductive connection from L1 to ground
B	Consumer		

7.3 RCD ground fault circuit interrupter



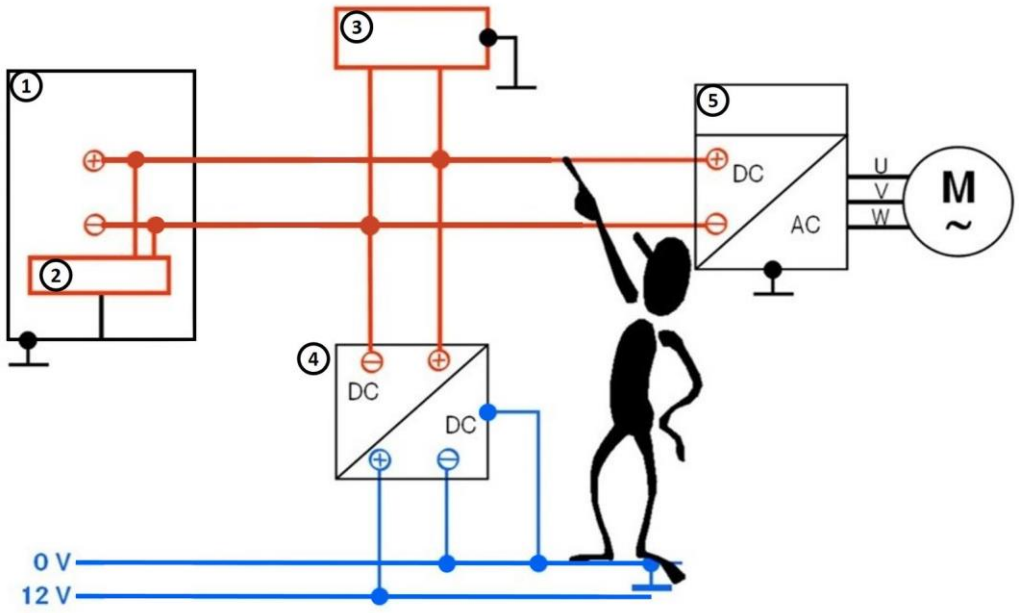
Ground fault circuit interrupters in the domestic network

GTT_013674

N	Neutral conductor	**C**	Household socket
PE	Protective Earth PE (protective ground conductor)	**D**	Person 1
L1	Phase 1	**E**	Person 2
A	Current/voltage source (power plant)	**F**	Consumer
B	RCD ground fault circuit interrupter		

7.4 Current fault in high-voltage vehicle

A high-voltage vehicle has no grounding like in an in-house installation. A further possibility of fault current detection must therefore be implemented in this so-called IT-like network.



IT-like network

GTT_013676

1	High-voltage battery	**4**	DC/DC converter
2	Insulation monitor	**5**	Power electronics
3	Other high-voltage components		

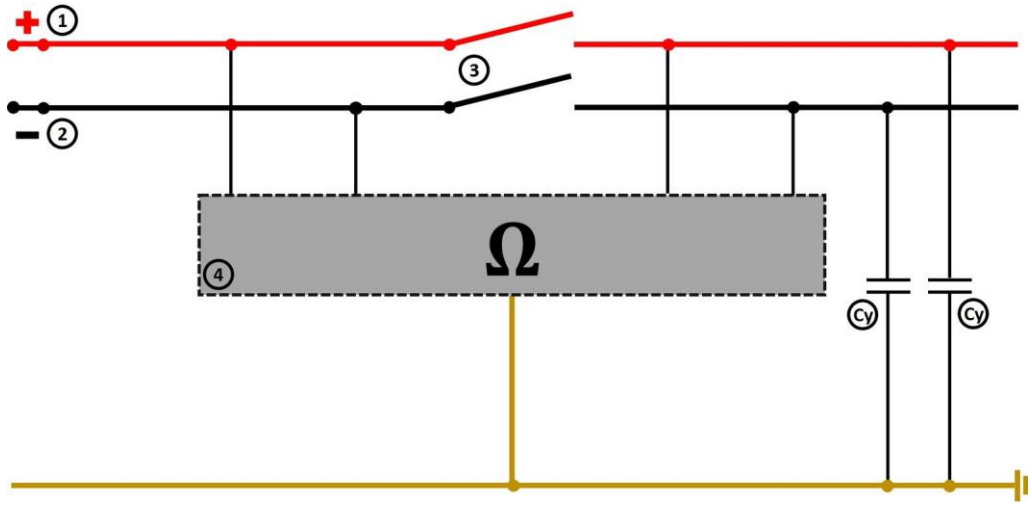
7.5 Insulation Monitoring

An insulation monitor is used in a high-voltage vehicle as a result of galvanic separation of the high-voltage on-board electrical system and vehicle ground. This component is tasked with monitoring the insulation resistance between high-voltage on-board electrical system and vehicle ground.

Within **ECE-R100** are the specifications for the high voltage system. This document states high voltage cables and components should be marked with yellow triangles and/or orange cables. As well as describing the separation of the high voltage system from the 12V system. The resistance specification for insulation monitoring that is given in the document is:

> 500Ω/V

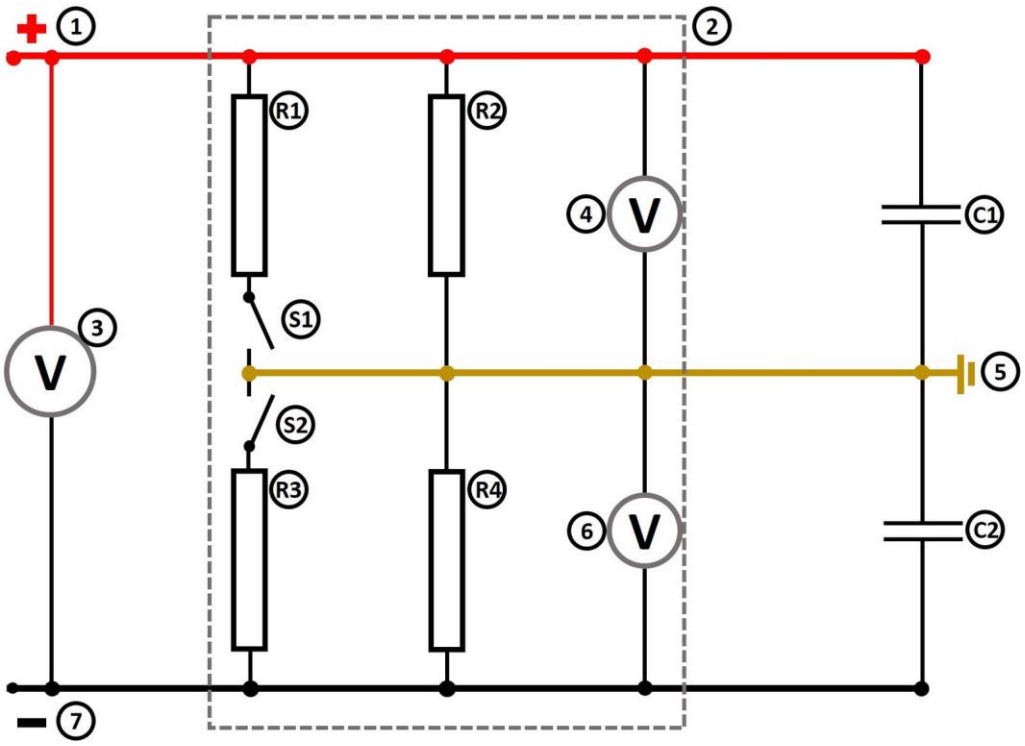
The insulation monitor measures upstream and downstream of contactors.



Insulation monitor

GTT_013678

1	HV+	**4**	Insulation monitor
2	HV-	**Cy**	Interference suppression capacitors
3	High-voltage contactors		



Insulation monitor – detail

GTT_013677

1	HV+	**C_2**	Interference suppression capacitor (–) (Cy)
2	Insulation monitor	**R_1**	Measuring resistance (+) (shunt)
3	Multimeter	**R_2**	Insulation resistance (+)
4	Multimeter (+) in the insulation monitoring	**R_3**	Measuring resistance (–) (shunt)
5	Vehicle ground	**R_4**	Insulation resistance (–)
6	Multimeter (–) in the insulation monitoring	**S_1**	Measuring resistance activation switch (+)
7	HV-	**S_2**	Measuring resistance activation switch (–)
C_1	Interference suppression capacitor (+) (Cy)		

Resistance shall be determined in an energized system. For this purpose, the insulation resistance is measured and calculated using voltage measurements at a shunt.

$$R_{ISOP} = \frac{U_{ISON1} * U_{ISOP2} - U_{ISOP1} * U_{ISON2}}{U_{ISON2}(U_{ISOP1} + U_{ISON1})} R_{SW}$$

$$R_{ISON} = \frac{U_{ISON1} * U_{ISOP2} - U_{ISOP1} * U_{ISON2}}{U_{ISOP1}(U_{ISON2} + U_{ISOP2})} R_{SW}$$

Formula for calculating the insulation resistance

GTT_013679

Group Work

Research the following questions using WIS and the Internet.

Then compare your results with the other groups and the trainer. Complete your notes.

1) Why is the insulation resistance in the megohm range and not infinite? What are the specified lower limit values?

2) What can lead to a deterioration of the insulation resistance?

3) How can you determine the insulation resistance?

4) Why is a multimeter not suitable for insulation resistance testing?

5) Perform a comparative measurement with a multimeter and an insulation resistance measurement device. Use the high-voltage cable provided by the trainer.

For your notes:

6) Where can fault currents occur in high-voltage vehicles?

   What effect do these fault currents have?

7) Describe the procedure for manually checking a possible fault current on the high-voltage vehicle. (Hint: see docs **AR47.70-P-1030-03A** and **AR47.70-P-1030EQS**)

7.6 Objective of equipotential bonding in high-voltage vehicles

One of the safety measures in high-voltage vehicles is the contact protection of live parts. A distinction is made here between direct and indirect contact protection of live parts.

- **Direct contact**

  Contact with live parts (active parts), e.g. a conductor. To prevent direct contact, active parts are provided with insulation or covers (basic protection).

- **Indirect contact**

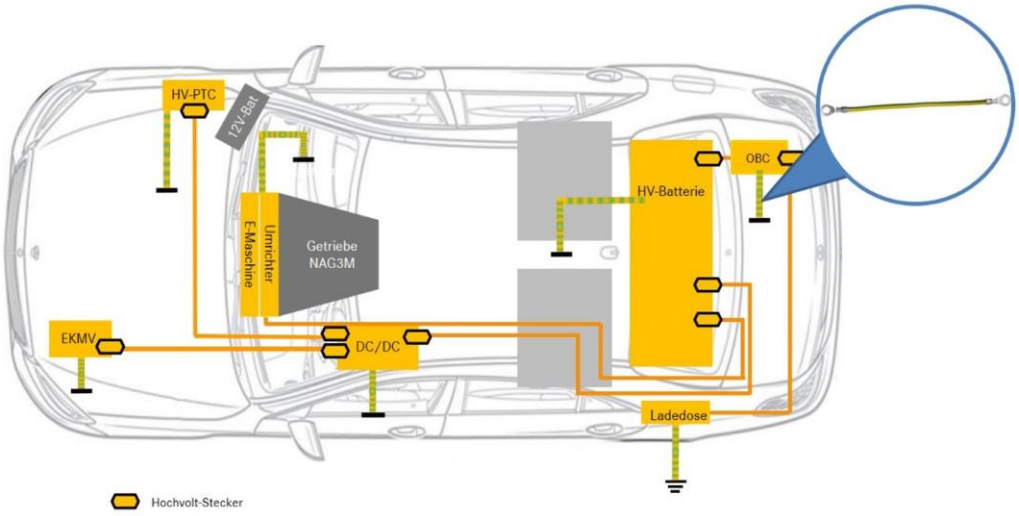
  Contact with bodies of electrical equipment that are under voltage as a result of a fault.

Equipotential bonding serves to protect against current shocks that can occur during indirect contact. It prevents the creation of a dangerous electrical potential between loose conductive parts, e.g. conductive housing, and a dangerous current flows through the body upon contact. For this purpose, the exposed conductive parts must be connected to the electrical ground in a galvanically secure manner. This is done either by current or ground cables or by welded or threaded connections.

Equipotential bonding:

Electrical connection that brings bodies of electrical machinery and equipment and foreign conductive parts to the same or almost identical potential.

Powerful electric motors in high-voltage vehicles generate strong, changing electromagnetic fields. These fields can induce voltages to the metal, conductive housing of the high-voltage components and to other conductive surfaces in the vehicle. This can result in potential differences between the individual components. In high-voltage systems, the current-carrying internal components are insulated from their housings. They are electrically isolated from them and therefore have no contact with the potentials of the housings. To enable equalization of these potentials, all high-voltage components in a motor vehicle are connected to each other and the vehicle body by a equipotential bonding line with sufficient cable diameter.



Equipotential bonding between the high-voltage components

GTT_013661

DC/DC	DC/DC converter
EFC	Electric refrigerant compressor
e-machine	Electric machine
High-voltage battery	High-voltage battery

HV PTC	High-voltage PTC
Vehicle socket	Charging socket
OBC	AC charger
Inverter	Power electronics, electric machine, high-voltage battery vehicle socket

⚠ CAUTION

All contact surfaces of the potential equalization must be clean and free of grease. Attention shall also be paid to corrosion and overcoating of the contact point, e.g. after refinishing.

The conductor cross-section must not be reduced by cable breakage. Consequence of high transitional resistances and cable breakage:

–> Increase in resistance

In the event of a fault, there is no protection from the equipotential bonding. A person working on the vehicle is exposed to the risk of high potential differences (potential flow through the body) between components.

Installation:
Check equipotential bonding line (3) for tight seating.
Otherwise, there may be danger to life and limb and operation of the high-voltage components without correct connection to the ground connection is forbidden.

Nm Bolt, equipotential bonding line to DC/DC converter

Installation:
Check contact areas for cleanliness.
Otherwise, there may be danger to life and limb and operation of the high-voltage components without correct connection to the ground connection is forbidden.

Measuring Equipotential Bonding

During the equipotential bonding measurement, the electrical resistance of these connections to equipotential bonding is checked. **According to ECE-R100, the resistance between all free conductive parts and the electrical ground shall be less than 0.1 Ω at a current of at least 0.2 A.** This requirement is considered to be met if the galvanic connection was achieved by welding.

When measuring the equipotential bonding, it is therefore important to measure the lowest transition resistances (in mΩ) to ensure that equipotential bonding can also bleed off the corresponding currents in the event of a fault. Since an exact measurement value in mΩ must be assessed here, the measuring cables shall not cause any measuring errors. Measuring equipotential bonding must therefore be carried out with a four-conductor resistance measuring device (milliohmmeter). The following practical tasks explain the operating principle of a milliohmmeter on the basis of the **METRAHIT 27 I** by Gossen Metrawatt GmbH.

Front axle power electronics control unit potential equalization measurement

1 Set insulation resistance meter for resistance test in mΩ area with 1 A pulse current (arrow A).

2 Insert measuring lines (1) into bushes (2, 3) of insulation resistance meter.

3 Clip Kelvin terminal of measuring line (1) onto corresponding measuring point (arrow B).

4 Clip Kelvin terminal of measuring line (1) onto corresponding measuring point (arrow C).

5 Use insulation resistance meter to check resistance between measuring point (arrow B) and measuring point (arrow C).

ℹ Specified value ≤ 10 mΩ

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7.7 Structure and operation of the milliohmmeter

Four-conductor resistance measurement

The four-conductor measuring method (also known as Kelvin measurement method) is used for exact and reproducible measurement of small resistances in the micro to milliohm range. It is used in particular if the undesired resistances of feed lines and contact points can distort the measurement. This is the case when the resistances of the feed lines and contact points are no longer insignificantly low compared with the resistance to be measured.

During four-conductor measurement, a known measuring current I_0 is fed in through the resistance to be determined R_x. The voltage U_x dropping at resistance R_x is picked up in the high-ohm range by two separate cables. According to Ohm's law, the resistance to be measured can be calculated from this:

$$R_x = \frac{U_x}{I_0}$$

The terminals for voltage measurement are connected directly at resistor R_x that is determined. As a result of the separate connection, the voltage drops via the contact and line resistances R_{kI} of the power cables do not have an influence on current measurement. In addition, voltage measuring cables are almost de-energized as a result of the high internal resistance R_U of the voltmeter. As a result, the voltage does not drop at voltage measuring contacts and cables R_{kU}. The measured voltage thus corresponds to the voltage at resistance R_x very accurately. Thus, neither the cables to the power supply nor voltage measuring cables influence the measurement result.

Kelvin Measurements

Kelvin measuring terminals enable an easy connection and offer a diversity of measuring options for a wide range of applications. To meet the conditions of four-conductor measurement and simplify the connection of four cables, two test contacts are attached in a terminal and insulated from each other. One contact set serves to supply current, the other serves to pick up potential. Kelvin measuring terminals offer a practical solution for making a four-conductor connection to cables, bus rails, electrodes, etc. and ensure a flawless and simple 4-pin connection of the measuring object.

7.8 Exercise 6: Hioki Measurements

- Describe how to use the Hioki 4 wire measurement tool.
- List the differences between using a DVOM and the Hioki 4 wire measurement tool for resistance measurements.
- Perform a resistance check on the equal potential bonding lines and determine if they are within specifications “ECE R 100” or “MB LV123”.

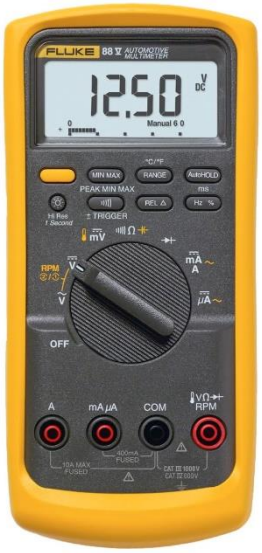
Needed for the exercise:

1 or 2 Hioki 4 wire measurement tools

4 Fluke DVOM’s

4 electrical kits

2 BEV or PH EV’s vehicles for measurements



Steps:

1. Connect the **red** and **black** leads to your DVOM and bridge the leads together and perform a resistance measurement of the leads and note your findings:

   _____

2. Now disconnect the **red** and **black** leads from each other . Set your DVOM meter on Amps and install your leads so you can read amperage with the DVOM.
   a. Turn on the Hioki and calibrate the meter and the leads using the Hioki in the 300 Ω range.

   b. When calibrating the Hioki make sure the leads for the Hioki are indexed correctly.

   c. Connect your Hioki leads to your DVOM leads and read the amperage the Hioki is putting out in the 300 Ω range on the DVOM. Note your amperage reading.

      _____

      Recalling what we learned about using meters. What is the best practice when measuring amperage?

      _____

   d. With the Hioki meter still connected to the DVOM, now using the range buttons on the Hioki select the following resistance ranges and note your amperage readings. **HINT,** don't forget to *use the high amperage range first before determining that you can use the milli-amp range.*

      i. 30 Ω _____

      ii. 3 Ω _____

      iii. 300 mΩ _____

      iv. 30 mΩ _____

      v. 3 mΩ _____

   e. Does the current output change on the Hioki 4 wire tester?

      ☐ **YES** ☐ **NO**

Explain your answer:

_____

_____

f. Measuring with the Hioki in the 300mΩ range what is the resistance of the DVOM including the test leads?

_____

_____

g. Measure just the resistance of the DVOM's **red** meter lead with the Hioki. What is the resistance?

_____

h. Measure just the resistance of the DVOM's **black** meter lead with the Hioki. What is the resistance?

_____

i. Calculate the internal resistance of the DVOM? _____

Open discussion with trainer:

3. With the 2 vehicles that are provided for you let's measure the equal potential resistance of the vehicles.

    a. Where do you put your meter leads when measuring the equal potential bonding lines?

    _____

    b. Please note here what your measurements were.

    _____

    c. Can you tell us if there is a problem with any of the equal potential bonding with the vehicles provided?

    _____

Open discussion with Trainer:

8 Magnetism

Magnetism is a natural phenomenon. Our earth has a geomagnetic field. The North Pole is located in the Arctic and the South Pole in the Antarctic.

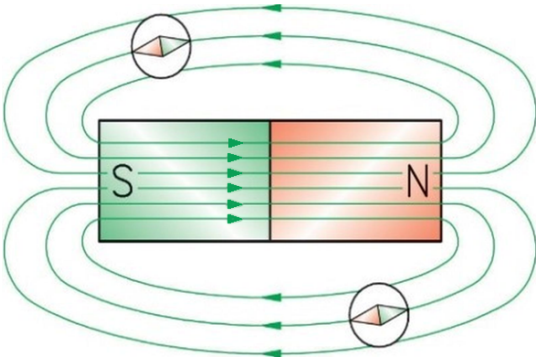


Figure 01-28 – Magnetic poles

GTT_010749

Ferromagnetic materials such as iron, nickel and cobalt can form magnetic fields as permanent magnets, similar to the magnetic field of the earth.
To manufacture particularly strong permanent magnets, “rare earth metals” such as neodymium, yttrium, lanthanum or cerium are needed. They are used in the following areas:

- Permanently excited electric motors
- Wind turbine generators
- Motors in electric and hybrid vehicles

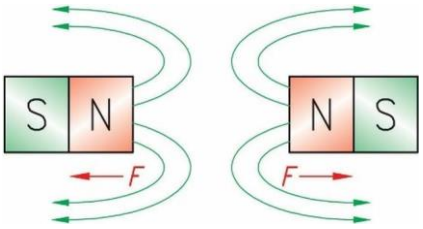


Figure 01-29 – Magnetic repulsion

GTT_010750

Equal poles repel each other.

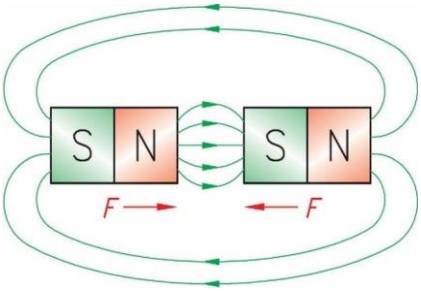


Figure 01-30 – Magnetic attraction

GTT_010751

Opposite poles attract.

In the model, the concept is that magnets consist of very many small molecular magnets.

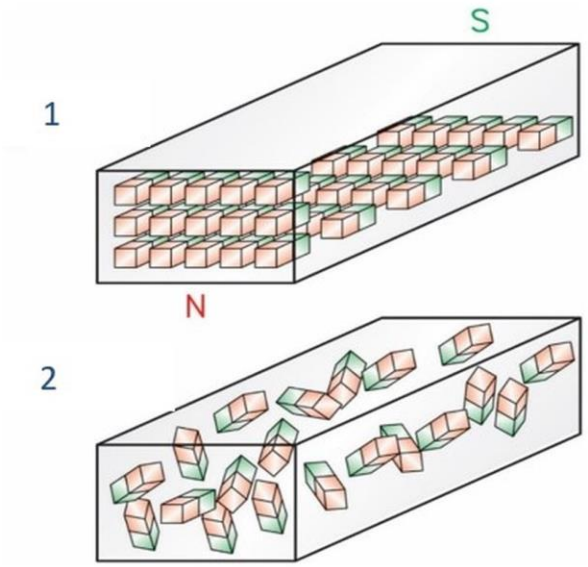


Figure 01-31 – Molecular magnets

GTT_010752

1	Ordered
2	Unordered

Magnetizing means that all elementary magnets are ordered to saturation. When demagnetized, this order is removed and the elementary magnets become disordered. This can happen by:

- Strong heating (glowing)
- Vibration
- Alternating magnetic fields

Magnetic field of a current-carrying conductor

As soon as a current flows through a conductor, a magnetic field Φ is created.

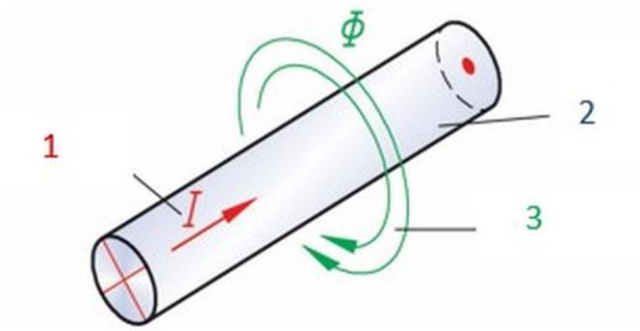


Figure 01-34 – Right hand rule

GTT_010755

1	Current (Technical direction)	**3**	Field lines
2	Electrical conductor		

Mechanical forces act on current-carrying conductors of this kind due to magnetism:

- If the current flows in the same direction, the conductors attract each other.
- If the current flows in the opposite direction, the conductors repel each other.

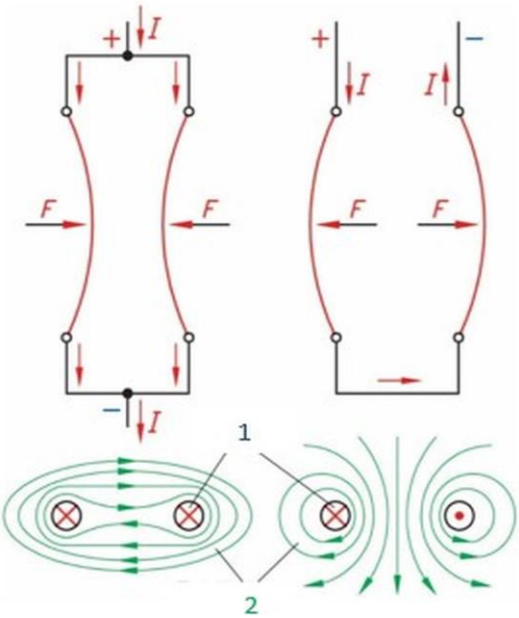


Figure 01-35 – Forces on current-carrying conductors

GTT_010756

1	Conductor
2	Field lines

8.1 The Electromagnet

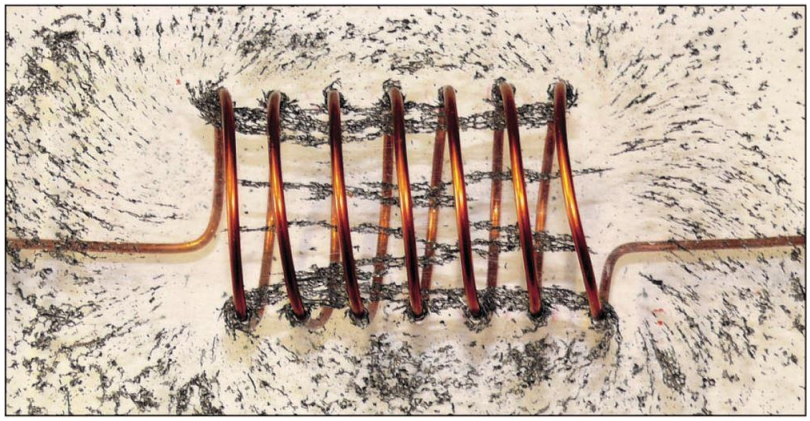


Figure 01-38 – Current-carrying coil

GTT_010759

An electromagnet is a conductor that has been wound into a coil. When it is energized, the field lines of the individual conductor loops add up and an electromagnet with a north and south pole is created.

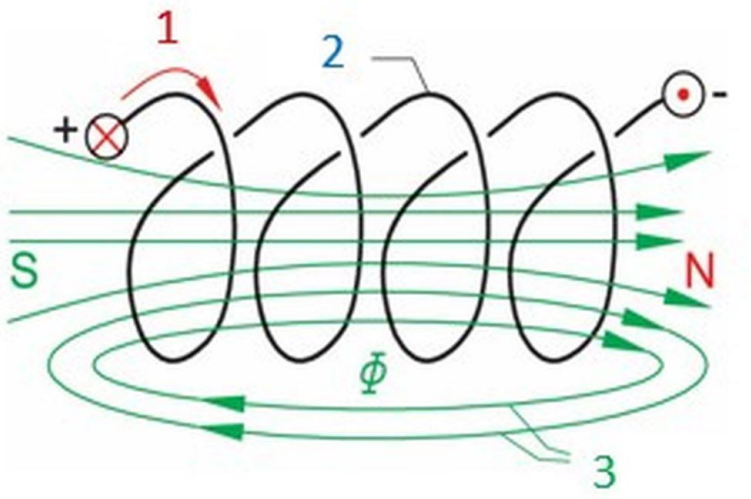


Figure 01-39 – Magnetic effect of a coil

GTT_010760

1	Current I	**3**	Field lines
2	Coil		

The greater the number of turns N and the current I of a coil, the greater the magnetic effect (= magnetomotive force Θ) of this coil.

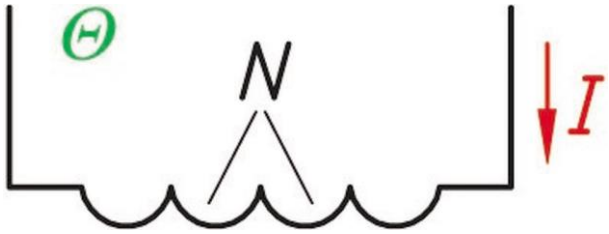


Figure 01-40 – Magnetomotive force

GTT_010761

$\Theta = I \times N$

Θ: Magnetomotive force

I: Current strength

N: Number of turns

The unit of magnetomotive force is given in A, because N has no unit. The magnetomotive force Θ is the cause of the magnetic field Φ.

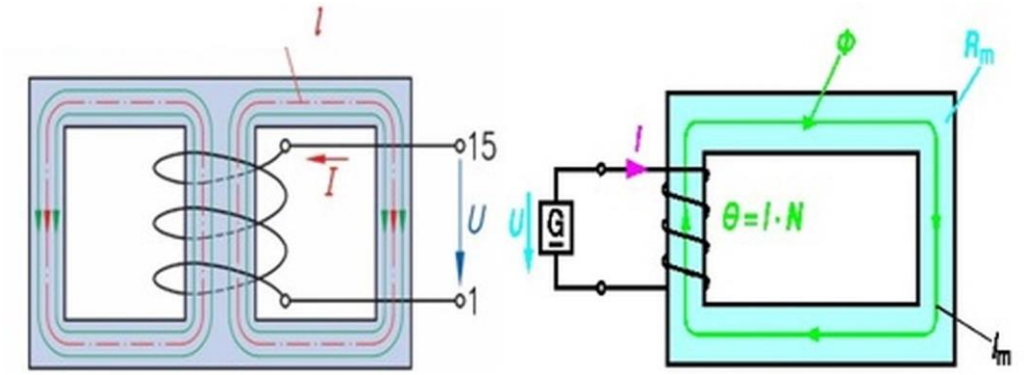


Figure 01-41 – Magnetic field strength where l = Mean field line length

GTT_010762

The henry (symbolized H) is the International System of Units (SI) derived unit of electrical inductance. Reduced to base SI units, one henry is the equivalent of one kilogram meter squared per second squared per ampere squared (kg m^2 s^{-2} A^{-2}).

The magnetic field strength H of a coil depends on the magnetomotive force Θ and the size of the coil (= field line length ℓ). The unit of magnetic field strength is given in A/m.

The field strength H is the cause of the magnetic flux density B.

$$H = \frac{\Theta}{\ell}$$

Self-induction voltage

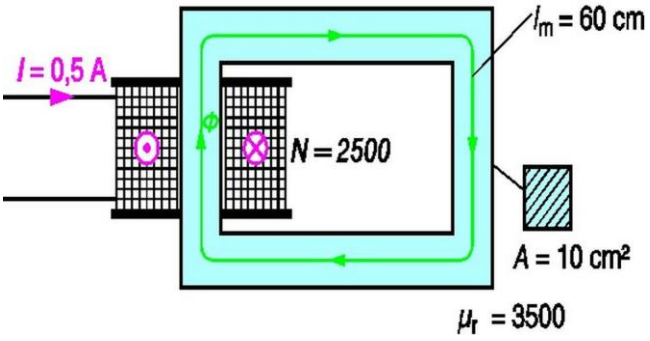


Figure 01-42 – Self-induction voltage

GTT_010763

The flux change Φ or current change over time is a measure for a voltage generated by induction itself. This voltage can be much larger than the operating voltage. It is opposite to the induction cause, hence the negative value.

$$Ui = -N \cdot \frac{\Delta \Phi}{\Delta t} = -N \cdot \frac{\Delta I}{\Delta t}$$

For this reason, it is problematic to switch inductors (coils). At the moment of switch-on, the voltage is present, but it takes a few fractions of a second for the magnetic field to build up. The switch-on current is limited only by the copper resistance of the wound coil. Because copper is a very good conductor, the switch-on current is very high. At the switch-off moment, a very high flux change or current change over time occurs. As a result, there is theoretically an infinitely high self-induction voltage. However, it is practically limited by the current flowing, the number of turns of the coil and the finite switch-off time.

In engineering, there are different methods to limit the switch-off voltage at coils, e.g. by:

- Freewheeling diodes
- R-C (resistor–capacitor circuit) combinations
- etc.

9 Coils

Interconnection of Inductors

Coils or inductors can be connected in parallel and in series.

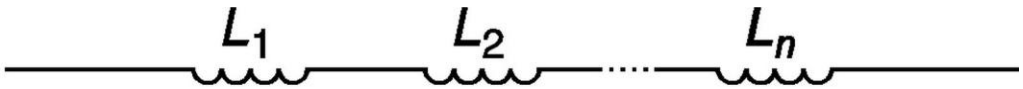


Figure 01-47 – Series connection of inductors

GTT_010768

When inductors are connected in series, the individual inductances add up

$L_{Total} = L_1 + L_2 + \ldots L_n$

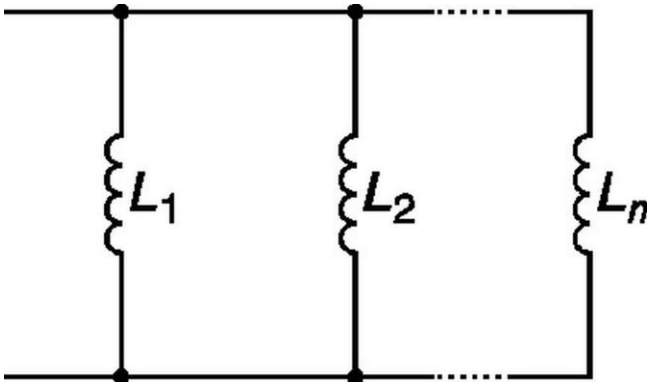


Figure 01-48 – Parallel connection of inductors

GTT_010769

When inductors are connected in parallel, the total inductance is reduced.

$$L_{gesamt} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n}}$$

Thus, coils behave like ohmic resistors.

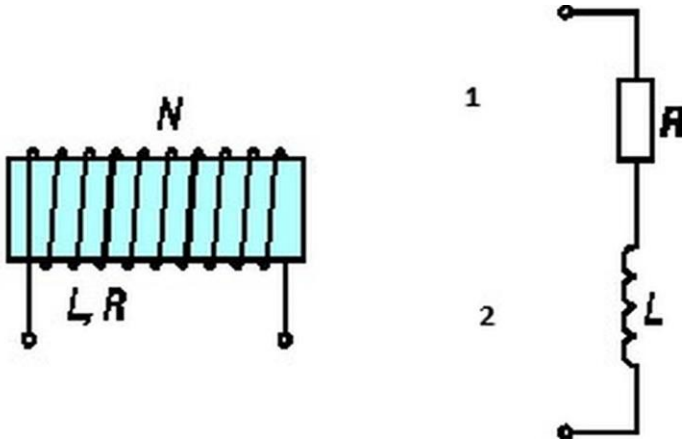


Figure 01-49 – Equivalent circuit diagram of a coil

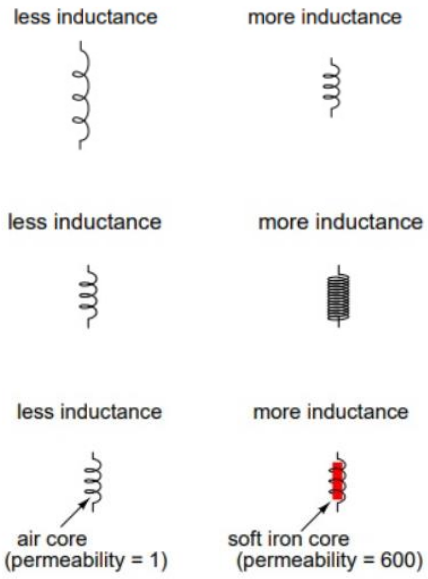
GTT_010770

1	Wire resistor
2	Inductance

9.1 Factors affecting the inductance of a coil

The key factors that affect the inductance of a coil are:

- Coil length
  - All other factors being equal, the longer the coil's length, the less inductance; the shorter the coil's length, the greater the inductance.
- Number of windings
  - The inductance increases with the number of wire turns in the coil. Less inductance is produced by the coil having fewer wire turns.
- Permeability of core
  - All other factors being equal, the greater the magnetic permeability of the core which the coil is wrapped around, the greater the inductance; the less the permeability of the core, the less the inductance.



9.2 Transformer

Transformer – Design and function

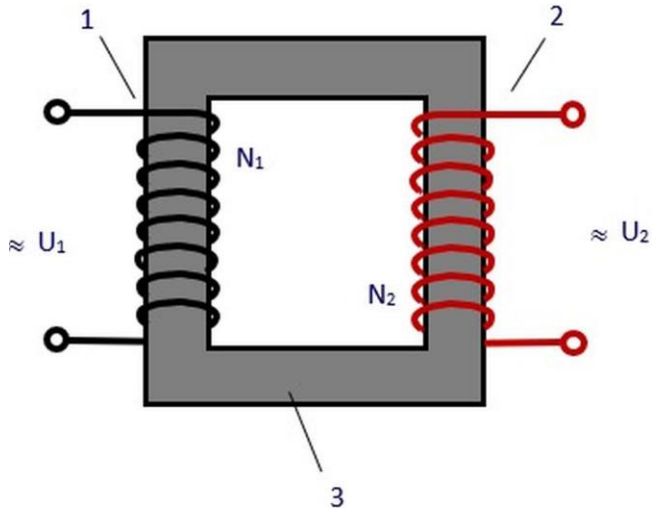


Figure 02-08 – Design: Transformer

GTT_010813

1	Primary coil	**3**	Closed iron core
2	Secondary coil		

Transformers essentially consist of at least two coils, a common iron core and, depending on the application, a cooling system.

In the simplest case, a transformer is made up of two coils. A distinction is made between the primary side of the transformer, to which the input voltage is applied, and the secondary side, from which the output voltage can be taken. The coil at the input is called the primary coil and the one at the output is correspondingly called the secondary coil.

The secondary coil can consist of several individual coils. These make it possible to generate several voltages on the secondary side of the transformer with one input voltage.

The coils are located on an iron core. It can be made of pressed iron powder, ferrite or silicon steel alloys. The winding of both coils on the core creates a magnetic coupling between them.

In high power applications, transformers must be cooled. Usually, transformers are cooled in an oil bath, with the oil also taking on the role of insulator against the outside world. It insulates better than air.

9.3 Task of Induction

As we have seen, induction can be used in many different ways, for example:

- Voltage conversion in a converter
- Galvanic separation
- Detection of rotor position and motor speed

9.4 Exercise 7: Calculation of the Step-up Transformer

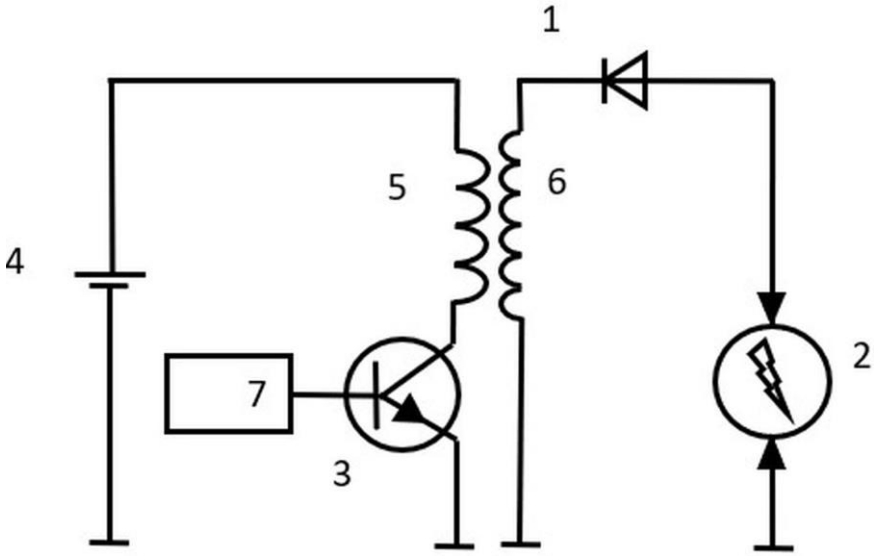


Figure 02-09 – Ignition coil

GTT_010814

1	Blocking diode	**5**	Primary coil
2	Spark plug	**6**	Secondary coil
3	Transistor	**7**	Control unit/ECU
4	Battery		

Objective:

Here we will practice using the formula to calculate a step-up transformer using the example of an ignition coil.

Output coil windings (secondary) are divided by the input coil windings (primary) and multiplied by primary coil voltage.

Calculate the voltage U_2 of the secondary coil.

The following variables apply:

Primary coil N_1 = 100 turns
Secondary coil N_2 = 25,000 turns
Voltage U_1 = 10 V

Formula to help: $U_2 = N_2/N_1 \times U_1$

9.5 Exercise 8: Calculation of the Step-down Transformation

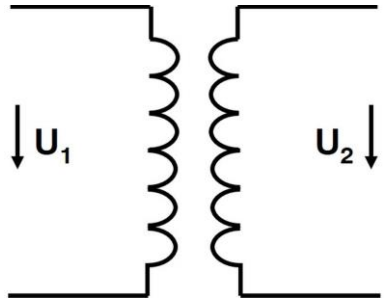


Figure 02-10 – Transformer

GTT_010815

Objective:

Here we will practice using the formula to calculate a step-down transformer using the given turns of the two transformer coils and a given input voltage. This will form the calculation before we build the circuit next to verify our calculations.

Calculate the voltage U_2 of the secondary coil.

The following variables apply:

Primary Coil N_1 = 900 turns
Secondary Coil N_2 = 300 turns
Voltage U_1 = 10 V

Formula: $U_2 = N_2/N_1 \times U_1$

Reminder to calculate AC voltage we need formula to go between Peak and RMS and vice versa.

When we look at an oscilloscope, we typically measure the peak or amplitude, so to calculate this to an RMS of effective voltage we use the following:

U_{EFF} or RMS = Peak (amplitude) x $1/\sqrt{2}$ or 0.707

9.6 Exercise 9: Step-down transformation

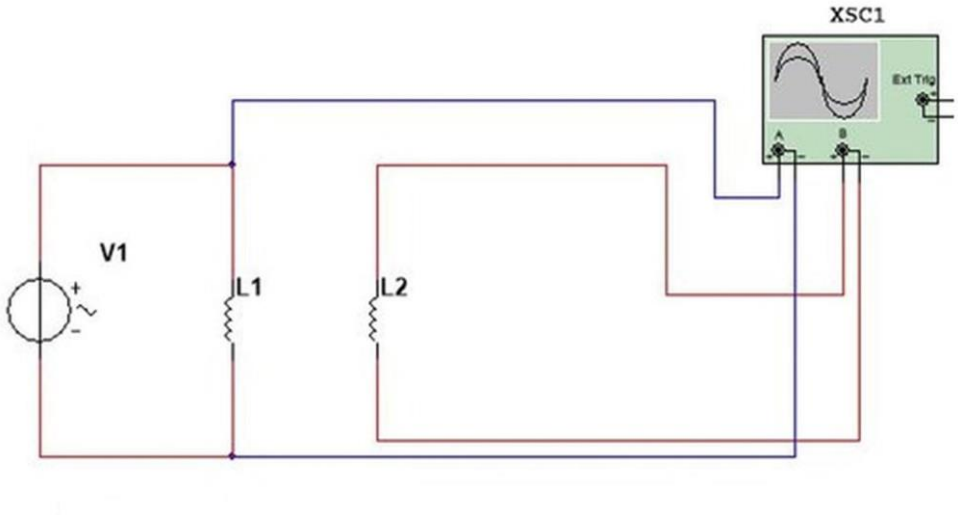
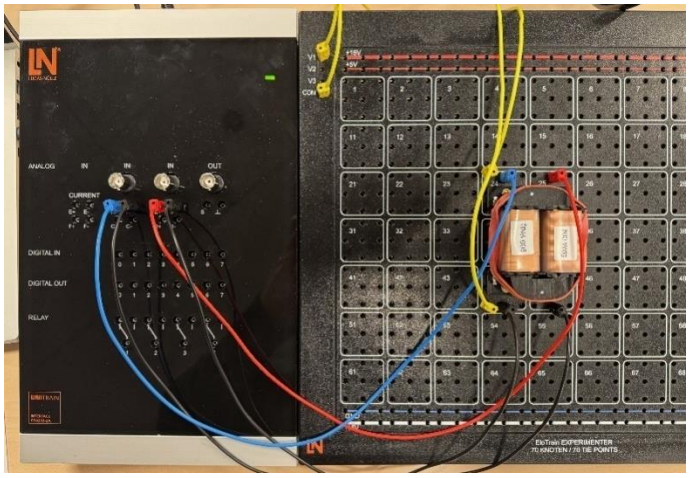


Figure 02-11 – Circuit diagram: Step-down transformation where L_1 = 900 turns and L_2 = 300 turns

GTT_010816



Objective:

Caution – When building this circuit, the transformer coils can be very difficult to insert due to the pin spacing. The Trainer will offer a tip which requires removing the elastic band and the iron cores and reorientating the coils and reassembling. It is possible that this has already been done before in a previous group, but this can be awkward. Also, be sure to rewrap the elastic band as the iron cores may fall out and possible break.

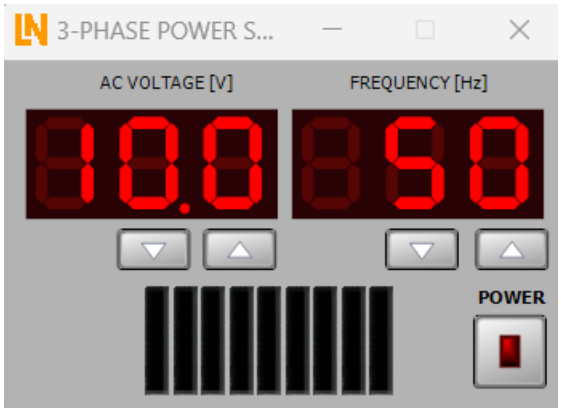
In addition, be very careful with your connections on the board, you may need to place a white connector in the board first before inserting the transformer coils.

Once built, we can verify our calculations in the previous exercises and further understand a step-down transformer.

On the instruction of your trainer, set up a circuit in the UniTrain I training system according to the figure. Complete the measurement values in the gaps provided under Figure 02-14.

The following devices and values are to be used:

- 3-Phase power supply (V1 and COM port)
- **N_1 = 900 turns** (component L1 in diagram)
- **N_2 = 300 turns** (component L2 in diagram)
- U_{1eff} = 10v
- f = 50 Hz



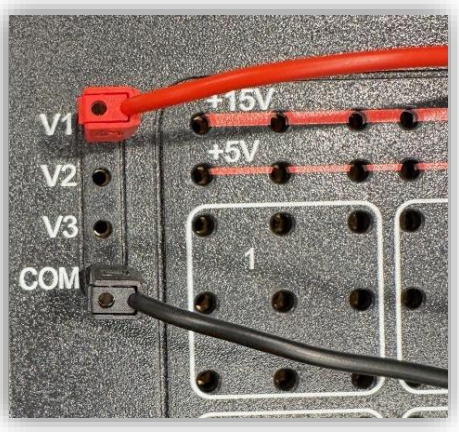


Figure 02-13 – Power supply setting

GTT_010818

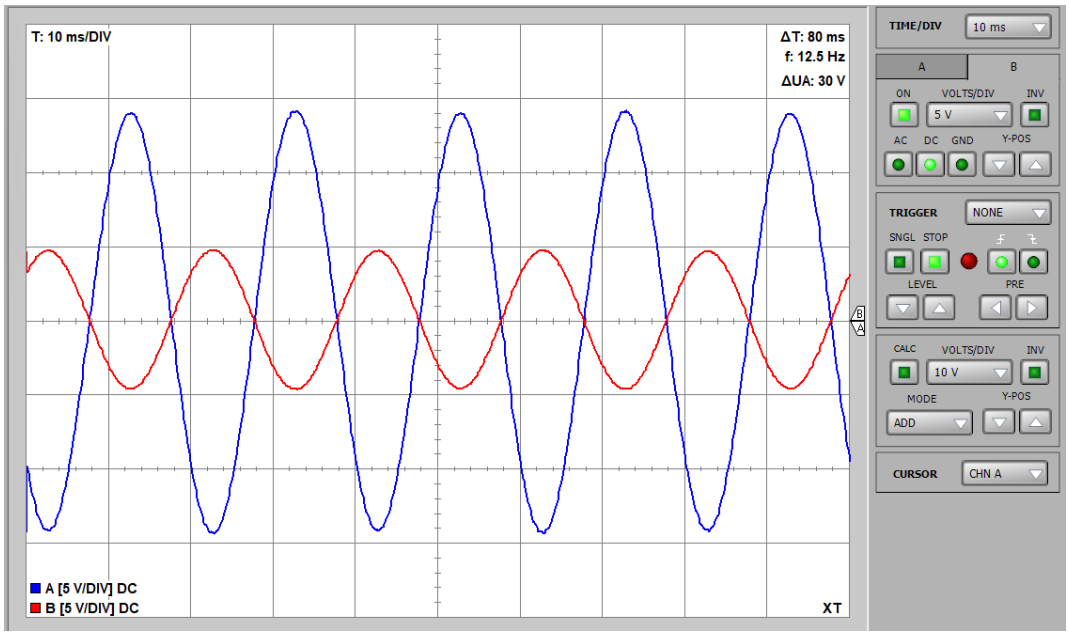


Figure 02-14 – Step-down transformation measurement

GTT_010819

Measurement of U_1 and U_2 with the oscilloscope

Channel A (blue) U_1 Amplitude = >>> U_{1eff}=

Channel B (red) U_2 Amplitude = >>> U_{2eff} =

9.7 Exercise 10: Step-up transformation

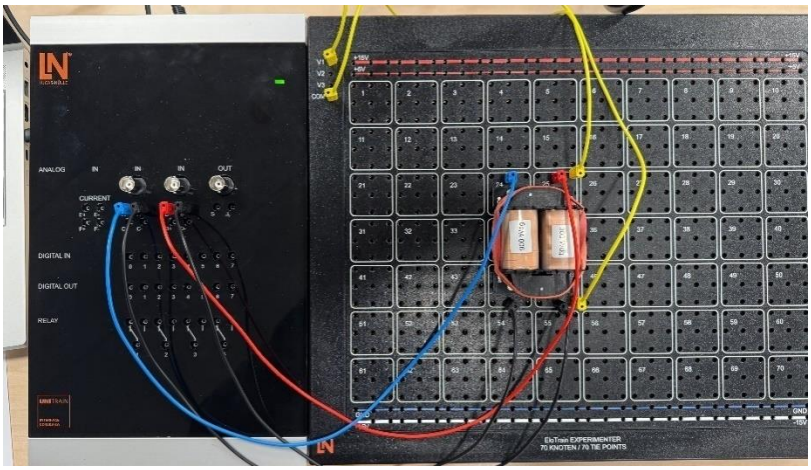


Figure 02-16 – Setup: Step-up transformation

GTT_010821

Objective:

Once built, we can verify our calculations in the previous exercises and further understand a step-up transformer.

Now we are going to swap our power input leads to provide power to the smaller coil (300)

Proceed according to your trainer's instructions for this exercise. Complete the measurement values in the spaces provided under Figure 02-18.

The following devices and values are to be used:

- 3-phase power supply (V1 and COM port)
- **N_1 = 300 turns** (component L1 in diagram)
- **N_2 = 900 turns** (component L2 in diagram)
- U_{1eff} = 4.0 V
- f = 50 Hz

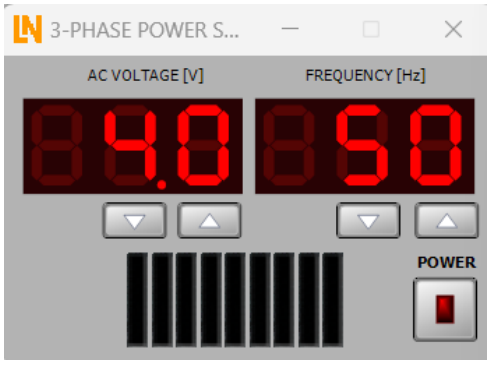


Figure 02-17 – Power supply setting

GTT_010822

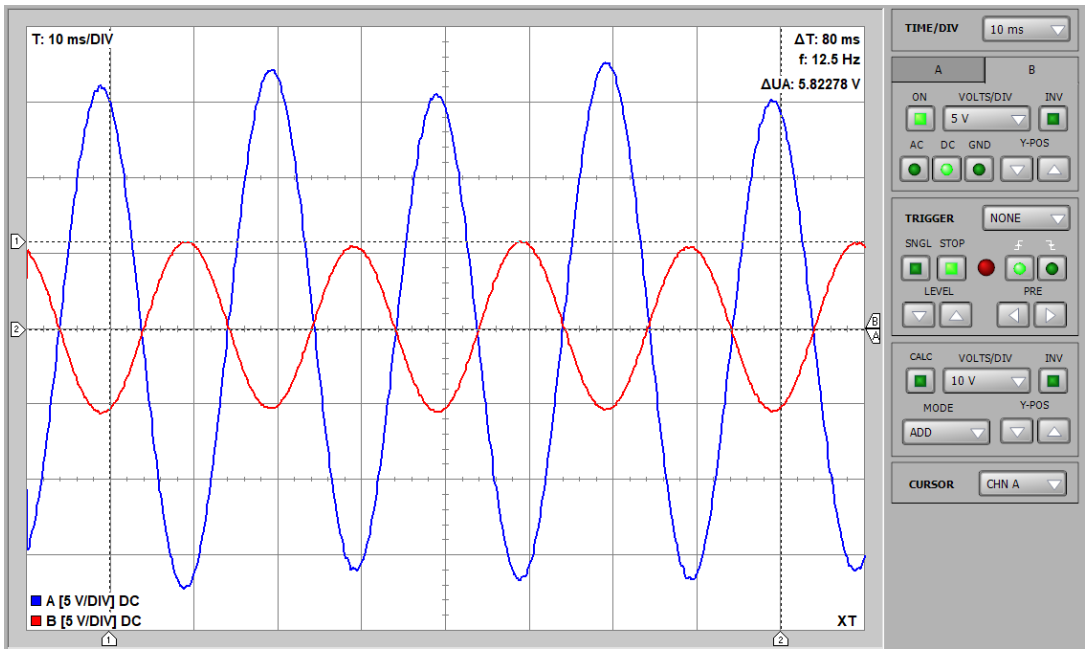


Figure 02-18 – Step-up transformation measurement

GTT_010823

Measurement of U_1 and U_2 with the oscilloscope

Channel A (blue) U_1 Amplitude = >>> U_{1eff}=

Channel B (red) U_2 Amplitude = >>> U_{2eff} =

9.8 Galvanic separation

Introduction

Galvanic separation is electrical isolation between two electric circuits. Thus, with this separation, it is not possible for the charge carriers to flow from one electric circuit to the other. There is no conductive, electrical connection between the electric circuits.

There are several options for galvanic separation:

- Optocoupler

  Separation via optocouplers is an information transmission which is realized by non-electrical transmission paths.

- Capacitors

  Capacitors result in capacitive separation, which means that a charge shift takes place.

- Transformers

  This results in an inductive separation and the transmission takes place via the detour of a magnetic field through the charge shift.

Galvanic separation is used in the following application examples:

- Toys

  Safety from electric shock

- Mains-powered extra-low voltages

  Safety from electric shock in connection with voltage conversion

- Chargers

  Safety from electric shock in connection with voltage conversion

- Medical devices

  Safety from electric shock in connection with voltage conversion with simultaneous isolation of the devices from the electric circuit

- Measurement technology

  Separation of the measuring devices from the electric circuit by the power supply

- Prevention of electromagnetic interference

- Automotive engineering

  Disconnection of the high-voltage system from the on-board electrical system

Galvanic separation is an efficient form of protection against electromagnetic interference. Long cables can pick up interference without a conductive power connection and pass it on to signal inputs. Protection against these radiated electromagnetic waves is improved by isolating signal inputs.

Isolating Transformer

Galvanic separation is very frequently used in energy technology as a safety precaution. Generally, 1:1 isolating transformers with safe isolation are used here.

Safe isolation means that the primary winding and secondary winding are designed separately and are separated from each other, are only connected to each other via an iron circuit (core) and, depending on the design, can be short-circuit proof.

Examples

- VDE REGULATION: ISOLATING TRANSFORMERS IN TANK CONSTRUCTION

  A worker crawls into a metal container with an electrotechnical device (drill). The electrotechnical device has a fault but the worker is protected with the help of the isolating transformer, because the fault does not allow current flow to the potential earth. The electric circuit is not closed.

  Only when the worker tries to attack the forward and return conductors of our secondary winding, like our light-emitting diode, can a current flow.

- ECE-R 100 REGULATION FOR ELECTRIC DRIVES CONSISTING OF SEPARATE DIRECT CURRENT OR ALTERNATING CURRENT BUSBARS

  If alternating current and direct current high-voltage busbars are galvanically isolated from each other, the insulation resistance between the high-voltage busbar and the electrical ground, based on the operating voltage, must be at least 100 Ω/V for direct current busbars and at least 500 Ω/V for alternating current busbars.

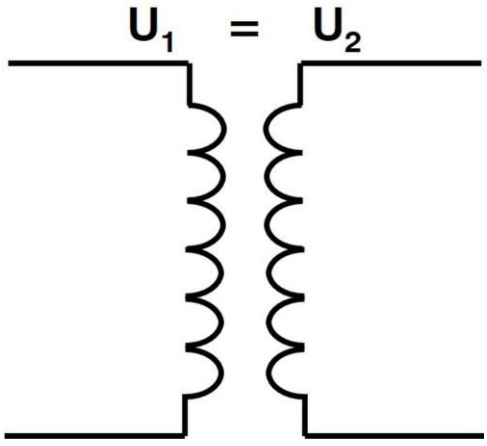


Figure 02-19 – Circuit diagram: Transformer as galvanic separation
GTT_010824

10 Capacitors

10.1 Design and Operation

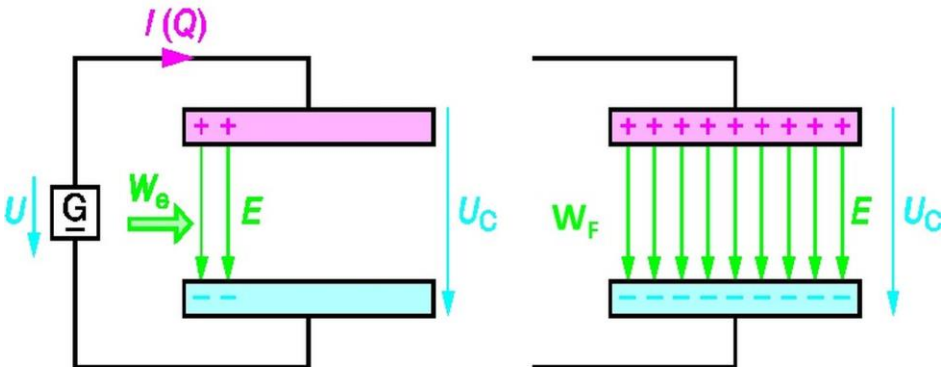


Figure 01-01 – Electrostatic field, $W_F = W_{Field}$

GTT_010722

What is a capacitor / role of a capacitor?

Basically, an electrical capacitor has two metal plates facing each other. If a voltage is applied to these plates, the charge carriers are separated, and an electrostatic field occurs.
The two metal plates have the capability of storing these charge carriers when the voltage is switched off.

The ability of the capacitor to store electric charges depends on the following factors:

- Plate area
- Distance between the plates
- Material between the plates, dielectric

This storage capacity is called capacitance. It can be calculated as follows:

$$[C] = \frac{A_s}{V} = F \qquad C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d}$$

$\varepsilon_0 \times \varepsilon_r$ = Material constants between the plates, dielectric

ε_r = Relative permittivity

ε_o = Electric field constant

A = Plate area

d = Distance between the surfaces

The formula letter for capacitance is designated **C** and has the unit **farad**.

The storage behavior of capacitors is also the reason for point 4 of the safety rules - grounding and short-circuiting. Capacitors within components present a safety risk as they can remain charged for long periods of time unless they are discharged through a process.

For high-voltage systems in motor vehicles, a waiting time must also be observed until the capacitor in the inverter input has discharged. There are also built in safety circuits within motor vehicles called active discharge and passive discharge.

As soon as a voltage is applied between two surfaces or a potential difference exists, an electrostatic field is created. In nature, for example, this occurs when water drops rub against each other, resulting in lightning against the earth if sufficient energy is available.

The dielectric strength of the medium in which the electrostatic field prevails is calculated as follows:

E = Dielectric strength	*[E] = Dielectric strength*
U = Voltage	*V = Voltage*
d = Distance between surfaces	*m = Distance between surface in meters*

$$E = \frac{U}{d} \qquad [E] = \frac{V}{m}$$

The dielectric strength of materials is usually specified in kV per mm which may be represented as:

kV/mm *or* . $\frac{kV}{mm}$

Air has a dielectric strength of approximately 3.3 $\frac{kV}{mm}$, depending on the humidity.

DANGER!

Electric shock, current passes through body

Severe burns, death

The safe distance of an electrician to an open electrical system under voltage (230 V or 400 V; public grid) must be at least 10 cm. Personal protective equipment, such as flame-retardant work clothing and face protection, must be worn.

A layman must maintain at least 1.5 m distance.

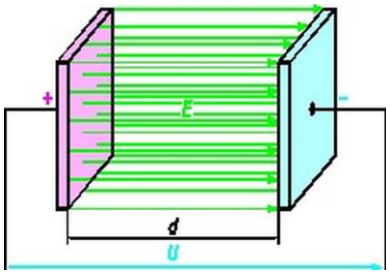


Figure 01-02 – Basic design of a capacitor

GTT_010723

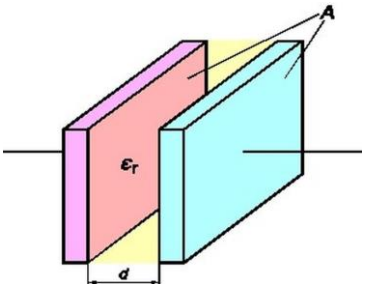


Figure 01-03 – Capacitance – Factors

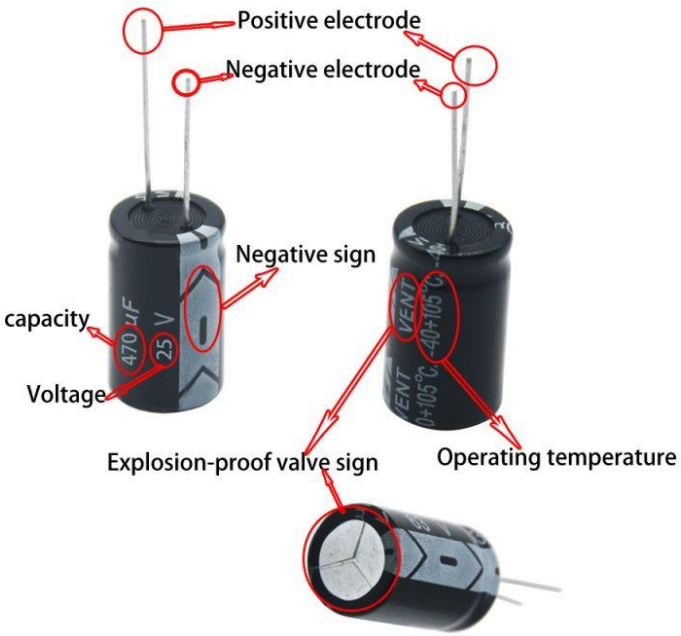
GTT_010724

Important: There are polarized and non-polarized capacitors.

Polarized capacitors have markings to indicate polarity for connection.

If these are not observed, then the capacitor will malfunction.

As an example, in the image below we can see typical markings on a polarized capacitor.



Below we can see examples of non-polarized capacitors.

Typically within diagrams . schematics we can see the symbol for a capacitor.

In addition we typically also see its Farad rating.

If the capacitor is polarized, we will see an indication of the correct polarity.

Example below:

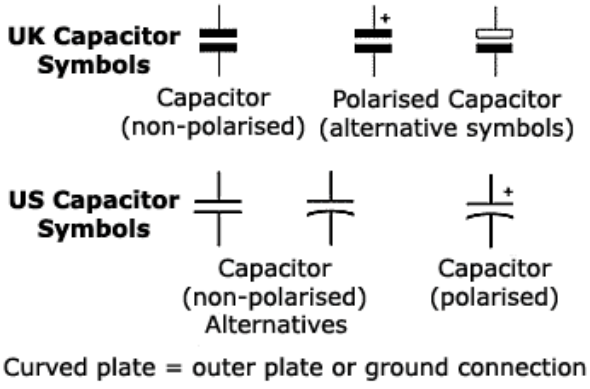
Figure 01-04 – Circuit symbol of an unpolarized metal-wound capacitor and a polarized electrolytic capacitor

GTT_010556

The above shows a typical **unpolarized** capacitor symbol on the left for a metal wound design for example. On the right we see a **polarized** capacitor symbol which may be an electrolytic capacitor design.

As we typically find, there may be other ways to indicate a capacitor in diagrams depending on the country and other factors.

Here, for example is a comparison between US & UK capacitor symbols. Note how similar they are, but also different.



10.2 Series and parallel connection of capacitors

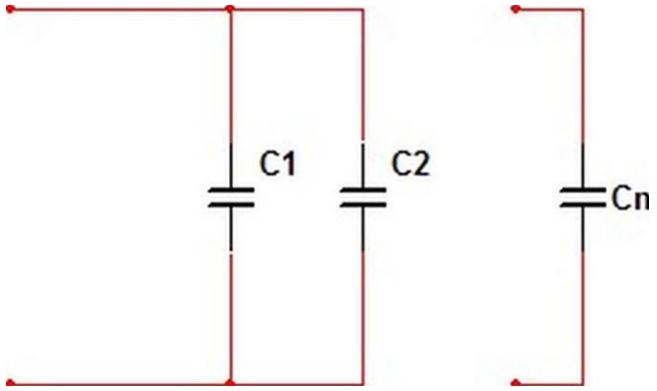


Figure 01-05 – Parallel circuit

GTT_010726

By connecting capacitors in parallel (shown above), the total capacitance is increased.

Gesamt is German word for Total.

The n in Cn is typical to use as an indication of further components, such as C_3, C_4 but unknown qty

$$C_{Gesamt} = C_1 + C_2 + \dots C_n$$

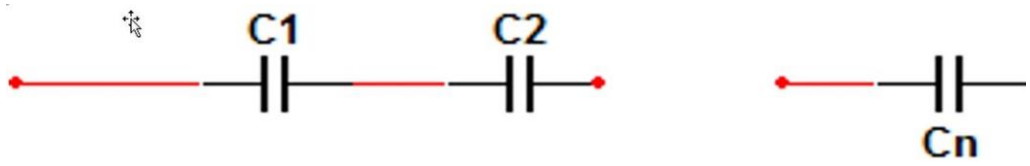


Figure 01-06 – Series circuit

The series connection (shown above), reduces the total capacitance.

TIP - Capacitances behave inversely to ohmic resistors.

$$C_{gesamt} = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \dots \frac{1}{Cn}}$$

10.3 Capacitor Types

The trainer will ask the participants to call out known types of capacitors.

Please use the space below to note down the initial list of capacitors the team identified:

Websites such as the one below are a great resources:

https://en.wikipedia.org/wiki/Capacitor_types

10.4 Capacitor Types and Applications

Capacitors with fixed capacitance (Fixed Capacitors)

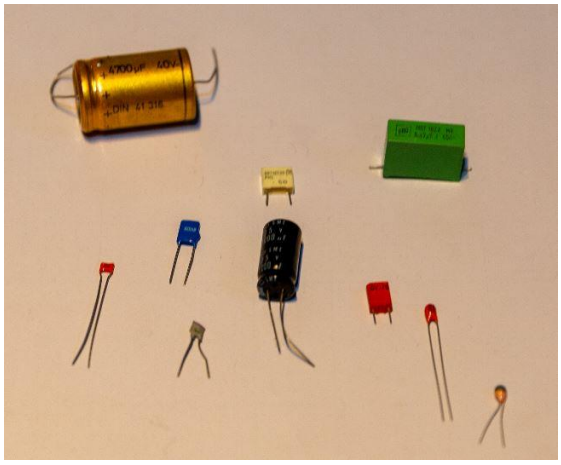


Figure 01-20 – Fixed capacitor

GTT_010741

Fixed capacitors have a fixed capacitance value. They are manufactured in various designs, depending on the technical requirements:

- Dielectric strength
- Maximum possible current
- Capacitance stability
- Temperature coefficient
- Operating frequency range
- Temperature range
- Mounting type (SMD version) *SMD = Surface Mounted Device*
- Economic requirements (price)

Their capacitance ranges from a few picofarads to about 100 microfarads for ceramic and plastic film capacitors, from about 1 microfarad to the farad range for electrolytic capacitors, to supercapacitors, which can have capacitance values into the kilofarad range.

Ceramic Capacitors

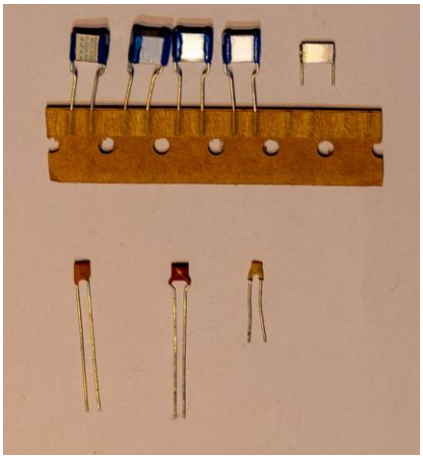


Figure 01-21 – Ceramic capacitors

GTT_010742

Ceramic capacitors form a large group of capacitors in the lower capacitance range from 0.5 pF up to 100 µF. Their dielectrics are made of ceramics, such as titanium dioxide (TiO_2) or barium titanate ($BaTiO_3$), with dielectric strengths from 10 up to 100,000 V. They are made from finely ground granules by sintering between 1200 – 1400 °C and are divided into two classes based on their electrical properties created by the different types of ceramics:

- Class 1 capacitors for high frequency and filter applications
- Class 2 capacitors for energy storage and as smoothing capacitors

Plastic Film Capacitors

In plastic film capacitors, the dielectric consists of plastic films or plastic blends.

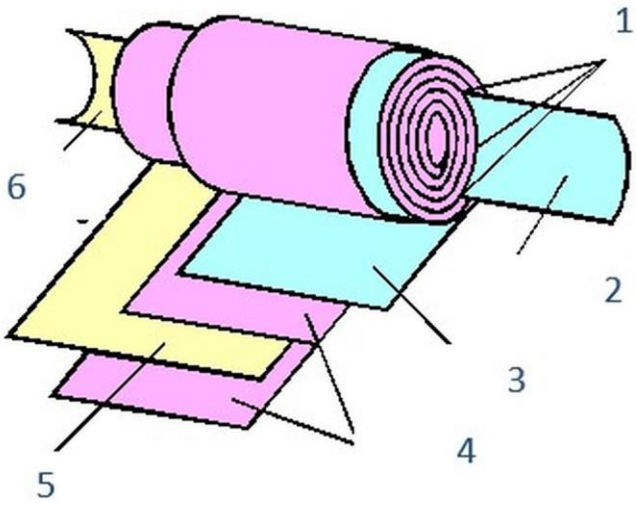


Figure 01-23 – Unpolarized wound capacitor

GTT_010744

1	Spot welds	**4**	Dielectric
2	Connection for 1st layer	**5**	Metal foil, 2nd layer
3	Metal foil, 1st layer	**6**	Connection for 2nd layer

These are manufactured in two versions:

- PLASTIC FILM CAPACITORS WITH METAL LAYERS

  They consist of two plastic films each, which are rolled up together with a metal foil to form a coil. The metal foils are contacted with the respective connection.

- METALIZED PLASTIC FILM CAPACITORS

  The plastic foils are each vaporized with aluminum on one side. These vaporized metal foils are in turn wound and contacted at the ends with the respective connection. This type of production is also found in layer capacitors. In them, several layers lie in one block. Metalized plastic film capacitors are self-healing in the event of a breakdown. The heat of the voltage breakdown arc vaporizes the thin metal layer around the breakdown channel.

Metal paper capacitors (MP capacitors)

They each consist of two strips of paper metalized with aluminum. The paper serves as insulation. Together with another piece of paper, they are rolled up into a coil and inserted in a cup. Impregnation with insulating oil increases the dielectric strength and reduces the loss factor. MP capacitors are used as power capacitors in power electronics and as interference suppression capacitors in mains applications. Just like the plastic film capacitors, they are self-healing.

Electrolytic capacitors

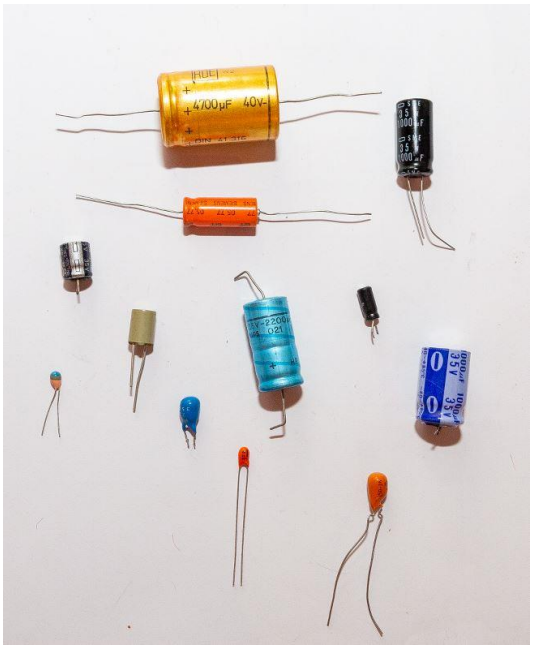


Figure 01-24 – Electrolytic capacitors

GTT_010745

Electrolytic capacitors are polarized capacitors whose anode consists of a metal (aluminum, tantalum and niobium). Electrolysis forms a thin, electrically insulating layer of the metal oxide of the anode material. This in turn forms the dielectric of the capacitor. Both solid and liquid electrolytes can be used here. It also forms the cathode of the electrolytic capacitor. Current is supplied to the electrolyte via foils of the same metal as that of the anode.

Electrolytic capacitors, with the exception of bipolar electrolytic capacitors, are always polarized components.

WARNING!

Risk of explosion

Destruction of the component, fire, risk of injury

Never operate with incorrect voltage polarity!
No overvoltage!

Double layer capacitors

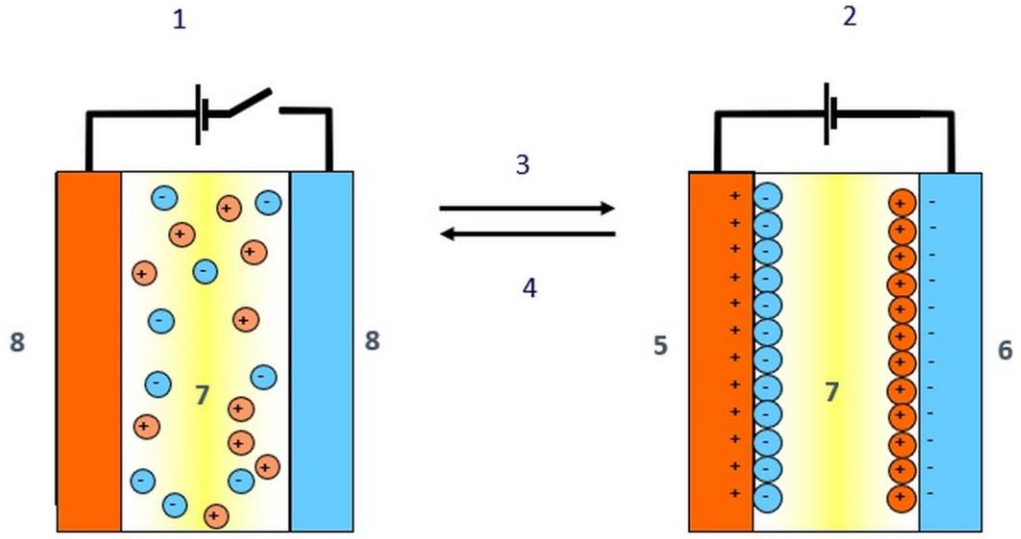


Figure 01-27 – Double layer capacitors

GTT_010748

1	Discharged	**5**	ANODE
2	Charged	**6**	CATHODE
3	Charge	**7**	Electrolyte
4	Discharge	**8**	ELECTRODE

They store electrical energy mainly in the Helmholtz double layers* of their electrodes.

**Helmholtz double layer is the combination of two layers of opposite charge around the colloidal particle. It represents the accumulation of electrical charges present at the boundaries of an electrolyte and electrode when they get in contact with each other.*

Their maximum share of pseudo capacitance is 10 % of the total capacitance.

Supercapacitors

Figure 01-26 – Supercapacitors

GTT_010747

They have the highest energy density of all capacitors. Their high capacitance, relative to the construction volume, is based on two physical phenomena:

Thin electrically insulating Helmholtz double layers on the surfaces of special large-area electrode materials. In them, the electrical energy is stored statically as double-layer capacitance in electric fields.

Another part of the high capacitance very often comes from "pseudo capacitance". This refers to a voltage-dependent electrochemical or faraday storage of electrical energy within narrow limits. This pseudo capacitance can achieve a significantly higher value than the double-layer capacitance with the same construction volume thanks to special electrodes.

10.5 Exercise 12: Capacitor Storage Behavior

Capacitors as energy storage units

- **When installing or connecting a polarized electrolytic capacitor, it is essential to observe the polarity. Destruction of capacitors with incorrect polarity!**

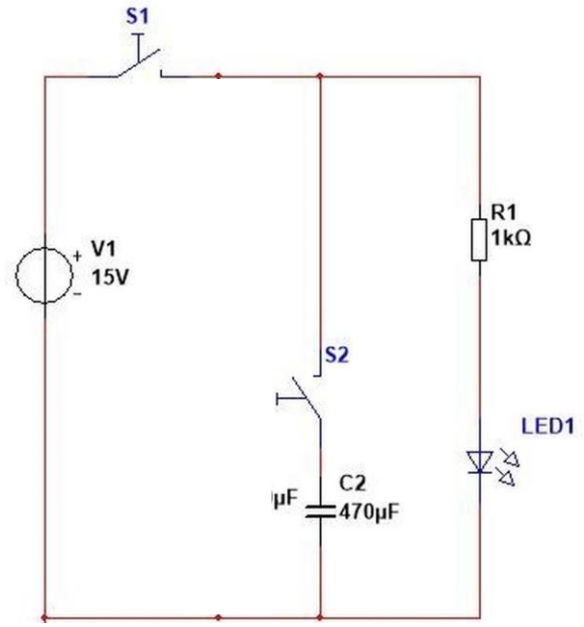


Figure 01-18 – Parallel connection of capacitors

GTT_010740

Objective:

This exercise will demonstrate the result of adding a capacitor in parallel to the load circuit. When power is interrupted to the load via the switch, we will experience different results depending on having a capacitor in the circuit or not.

Set up a circuit in the UniTrain I training system as shown in Figure 01-18. Use the following equipment and components for this purpose:

- UniTrain I
- Resistance R1 = 1 kΩ
- Capacitor C2 = 470 µF (Remember this is a **polarized capacitor**)
- S2 Toggle Switch
- S1 Pushbutton switch
- LED

With S2 open, observe the on/off time of the LED. Then close S2 and repeat. What did you notice?

Capacitors in parallel

▶ **When installing or connecting a polarized electrolytic capacitor, it is essential to observe the polarity.** **Destruction of capacitors with incorrect polarity!**

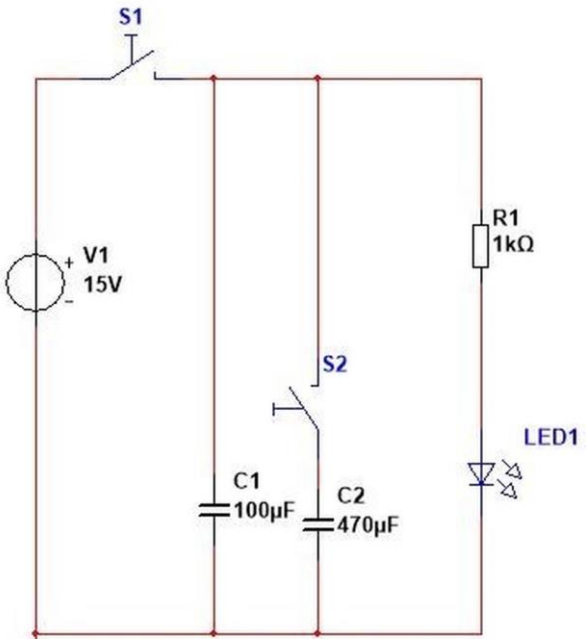


Figure 01-19 – Parallel connection of capacitors

GTT_010740

Objective:

This exercise will demonstrate the result of adding a capacitor in parallel to the load circuit. When power is interrupted to the load via the switch, we will experience different results depending on the size of the capacitor in the circuit.

Set up a circuit in the UniTrain I training system as shown in Figure 01-19. Use the following equipment and components for this purpose:

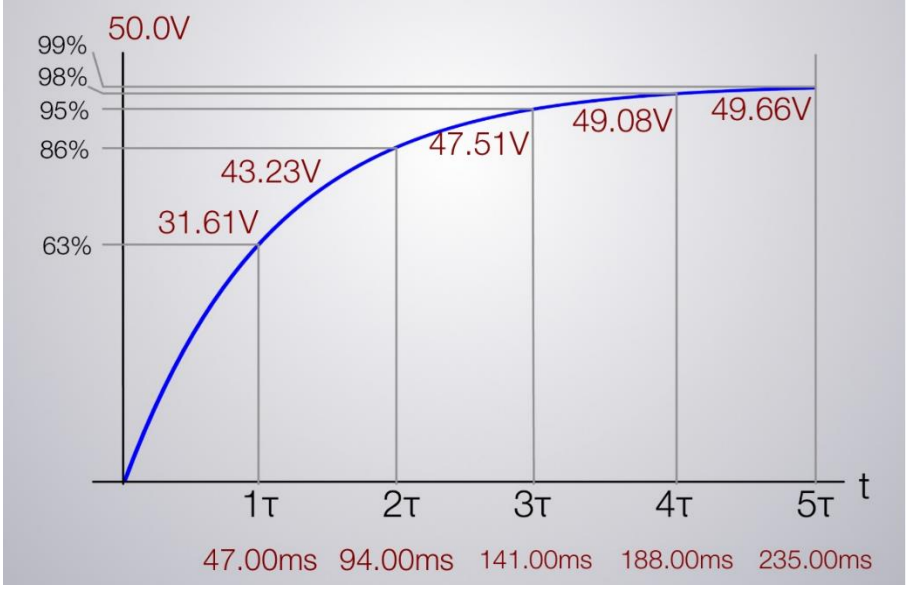
- UniTrain I
- Resistance R1 = 1 kΩ
- Capacitor C1 = 100 µF (Remember this is a **polarized capacitor**)
- Capacitor C2 = 470 µF (Remember this is a **polarized capacitor**)
- S2 Toggle Switch
- S1 Pushbutton switch
- LED

Measure the LED lighting time (stopwatch) first with one capacitor switched on and compare it with that with the second capacitor switched on. Document your results and discuss the cause of this behavior with the trainer.

You will notice that the LED lights up much longer when the capacitors are connected in parallel than when there is only one capacitor. The parallel connection of capacitors thus results in an increase in capacitance.

$C_{Total} = C_1 + C_2 \ldots + C_n$

10.6 Exercise 13: Capacitor Charging and Discharging Calculation



The above is just an example and will not match the results of your calculations.

Objective:

This exercise will have you calculate the charge and discharging times for capacitors and get you familiar with the terms used for this process such as Tau and the formula. In addition, we will also explore if voltage or circuit resistance plays any role in the charging and discharging time.

Please complete the following calculations to determine capacitor charging & discharging times.

This should be a refresher from the eLearning but as we have just seen, a capacitors rating can impact a circuits operation.

As a reminder the charging time is 5T. T is for TAU (time constant measured in seconds).

The formula to calculate T for capacitors charging is:

$$T = R \times C$$

R = Resistance of circuit for charging

C = Capacitance

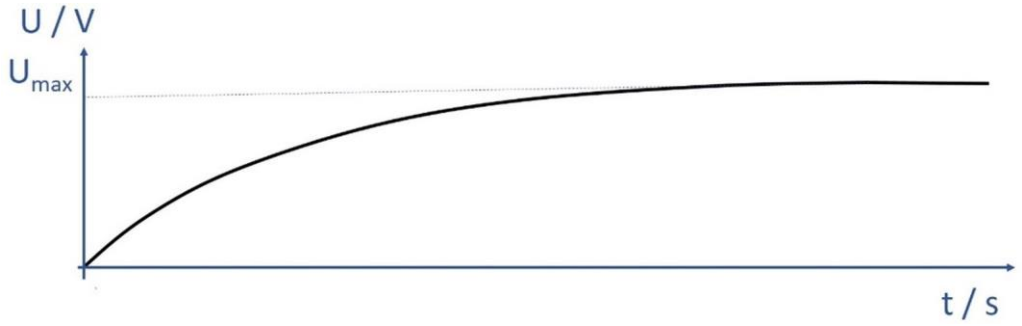


Figure 01-07 – Charging curve

GTT_010559

After a direct voltage is applied to a capacitor with series resistor, a uniform electric current flows. This causes the electrodes to be charged in opposite poles, resulting in a constantly increasing potential difference in the capacitor. When the voltage in the capacitor reaches the same level as the voltage of the voltage source, no more current flows. The capacitor is now charged.

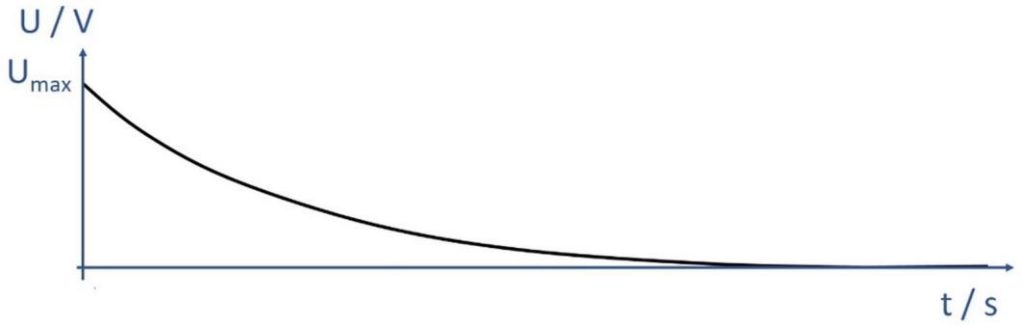


Figure 01-08 – Discharge curve

GTT_010560

If the capacitor is disconnected from the voltage source, the charge on the electrodes remains stored. During the discharge process, energy is removed from the capacitor, i.e. the field strength of the electric field decreases and with it the capacitor voltage.

Behavior of capacitors with direct and alternating voltage

Electro technically, a capacitor in a **DC circuit behaves like an absolute high-ohmic resistor**. The capacitor charges once, after which there is no more current flow. Therefore, a capacitor in the DC circuit is to be considered like an open switch or an infinitely high resistor.

For very high frequencies in the **AC range, the capacitor acts like a short circuit**.

Calculate the charging time for a 2000µF capacitor with a 100Ω resistor?

What will be the discharging time? Is it always the same as the charging time?

Does the voltage level affect the charging or discharging time?

For the same capacitor, what would the charging time be if the circuit resistance was 1 kΩ?

10.7 Exercise 14: Charging and Discharging Behavior of capacitors

⚠CAUTION

Destruction of capacitors with incorrect polarity

Fire hazard, risk of injury

- When installing or connecting a polarized electrolytic capacitor, it is essential to observe the polarity.

Objective:

This exercise will have you calculate the charge and discharging times for a capacitor in a circuit we will build and get you familiar with the calculation and also understanding the capacitors function within a circuit for charging and discharging.

Following the discussion of the curves, lets study the following circuit for charging a capacitor.

Shortly we will build this circuit but before building it we want to calculate what we should see and how long the charging and discharging will be.

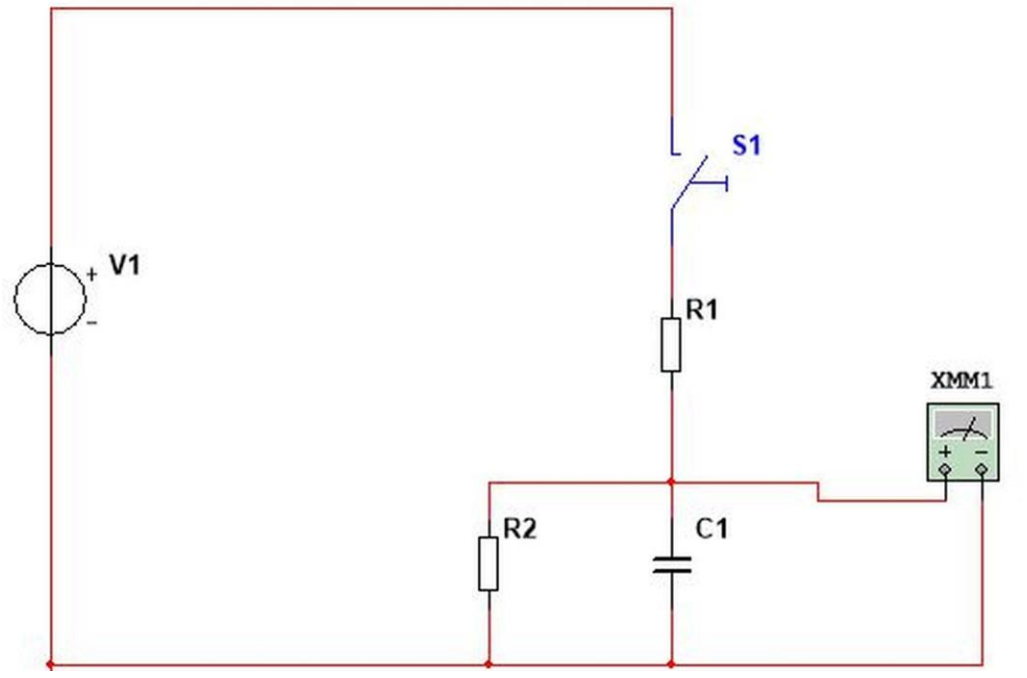


Figure 01-09 – Circuit diagram: Charging a capacitor

GTT_010730

Devices used:

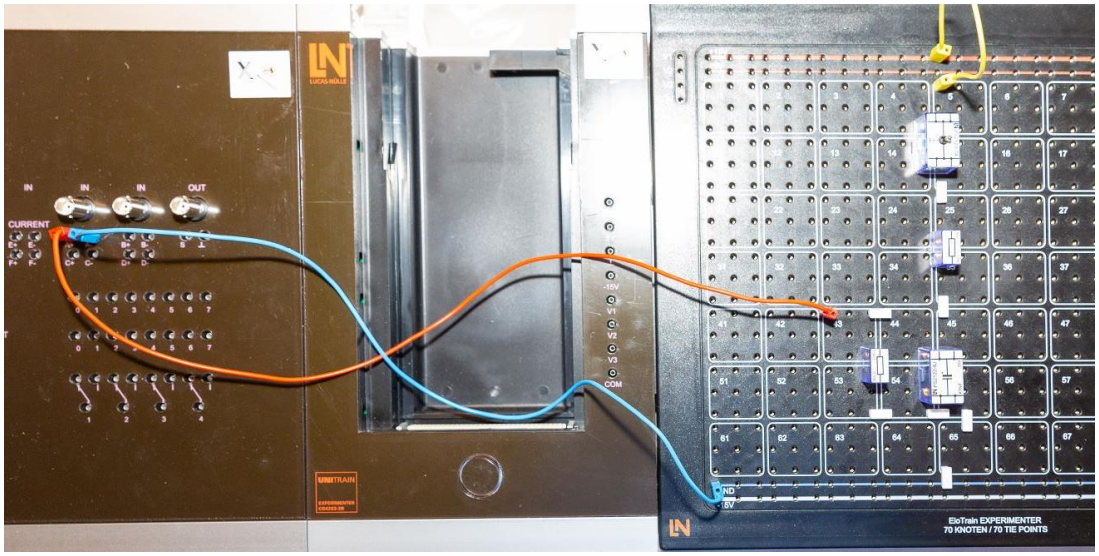
- UniTrain I
- Oscilloscope
- Resistance R_1 = 1 kΩ
- Resistance R_2 = 10 kΩ
- Capacitor C_1 = 470 µF
- S1 – Push Button Switch

Before building the circuit in Figure 01.09, please calculate the charging and discharging time for the specified capacitor and circuit.

Charging:

Discharging:

Are the charging and discharging times the same or different? Please explain?



Now build the circuit according to the circuit diagram and photo and connect the circuit to the 15V voltage source.

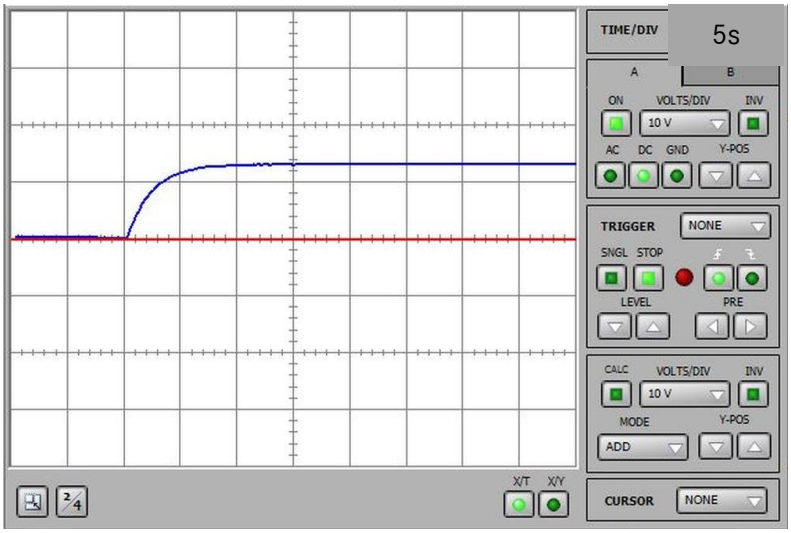


Figure 01-11 – Charging a capacitor

A) The oscilloscope is connected in parallel to the capacitor and the settings are made according to the above picture. Observe the measurement, note the results and discuss them in the work group.

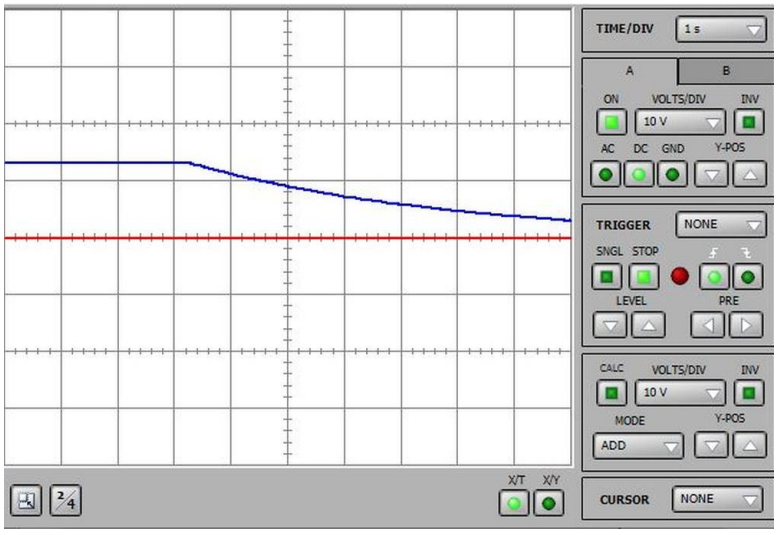


Figure 01-12 – Discharging a capacitor

B) On the instruction of the trainer, now discharge the capacitor with the power supply switched off via resistor R_2. Observe the measurement and discuss in the work group.

10.8 Exercise 15: Periodic Charging and Discharging of Capacitors

⚠CAUTION

Destruction of capacitors with incorrect polarity

Fire hazard, risk of injury

- When installing or connecting a polarized electrolytic capacitor, it is essential to observe the polarity.

Objective:

This exercise will have you examine the charge and discharge of a capacitor when a pulsed signal (Logic) is present. We will also see how the same or different capacitors perform with different frequencies and we should better understand that dimensioning a capacitor in a circuit depends on several factors including the signal frequency.

Now build the circuit shown in Figure 01-13 for charging a capacitor in the UniTrain I training system as instructed by the trainer.

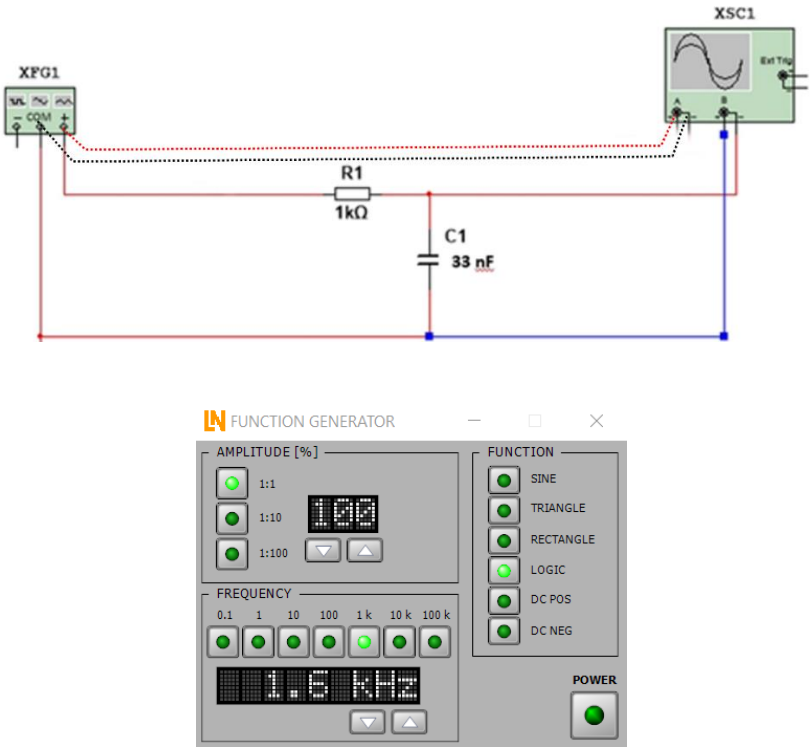


Figure 01-13 – Circuit diagram: Periodic charging and discharging of a capacitor

GTT_010734

Devices used:

- UniTrain I
- Function generator: U = 10 V (Logic Function)
- Two-channel oscilloscope: f = 1.6 kHz
- Resistance R_1 = 1 kΩ
- Capacitor C_1 = 33 nF

Figure 01-14 – Design: Periodic charging and discharging of a capacitor

GTT_010735

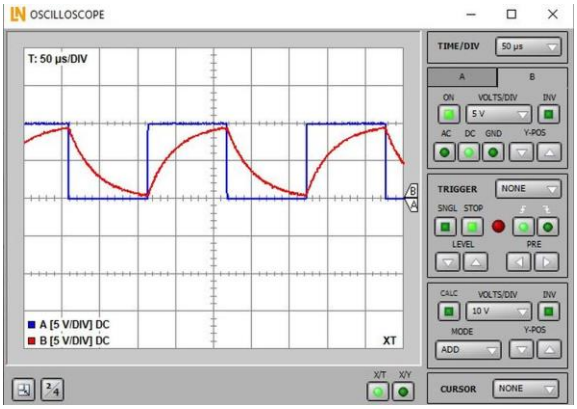


Figure 01-16 – Oscilloscope settings

GTT_010737

Oscilloscope settings:

- DC range
- Channel A 5 V/div
- Channel B 5 V/div
- Time base 200 µs/div

Display of oscilloscope:

- Channel A Input voltage
- Channel B Voltage curve at capacitor

The square wave function of the function generator periodically switches the input voltage on and off. The voltage curve across the capacitor is visualized on channel B.

At the switch-off moment, the storage behavior of capacitors can be seen. At the switch-on moment, it can be seen that the capacitor needs some time to charge up. This is called a time delay element.

Once you have seen this reaction, please change the frequency and see how the reaction of the capacitor may change. It may be necessary to go quite high with the frequency, but you should see a change to the capacitors ability to charge and discharge.

Make notes below of your observations:

Now try changing the capacitor to 1µF and repeat the experiment and note your observations below:

10.9 Exercise 16: Phase Shifting of Capacitors

⚠ CAUTION

Destruction of capacitors with incorrect polarity

Fire hazard, risk of injury

- ▶ When installing or connecting a polarized electrolytic capacitor, it is essential to observe the polarity.

Objective:

This exercise will have you examine the charge and discharge of a capacitor when a pulsed signal (Logic) is present. We will see how **current proceeds voltage** with the scope as we use the resistor as a shunt resistor. This is known as phase shifting and sometimes referred to as current proceeds the voltage by 90°.

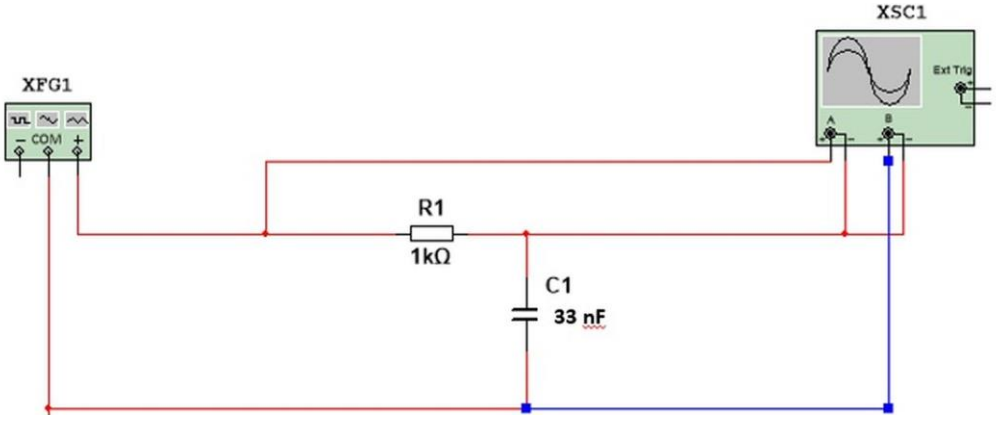


Figure 01-17 – Circuit diagram: Phase shifting

Function generator:

- U = 10 V
- f = 1.6 kHz
- Logic

Please note the change of Channel A connection compared to previous experiment.

In the circuit described above, the voltage across the capacitor is measured on channel B. On channel A, the voltage is measured across the resistor which is used here to take an indirect current measurement.

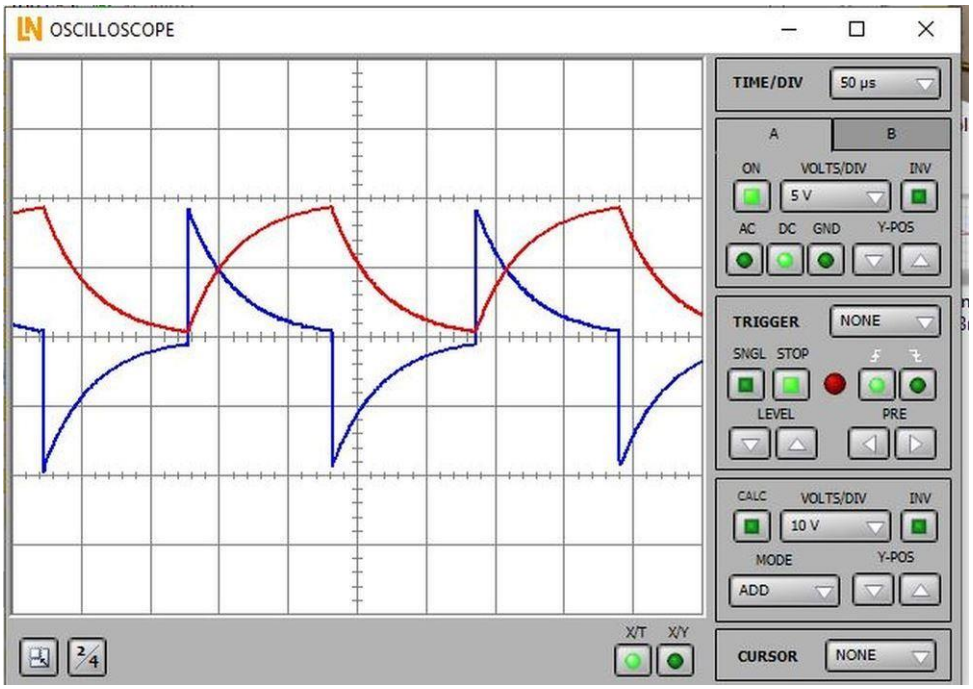


Figure 01-18 – Oscilloscope settings

GTT_010739

Oscilloscope settings:

- DC range
- Channel A 5 V/div
- Channel B 5 V/div
- Time base 200 µs/div

Due to the relocation of channel A connections across the resistor R_1, we will be measuring voltage drop across the resistor R_1. When the supply voltage is in its off state, the capacitor discharges through the resistor R_1. When the supply voltage is switched on, the capacitor is charged via resistor R_1.

Essentially this represents a measurement of the current curve, since the resistor R_1 serves as a shunt resistor.

In the experimental setup (Figure 01-17), a shift of current and voltage at the capacitor can be seen on both channels.

The current precedes the voltage by 90 degrees. This effect is called phase shifting.

STOP

10.10 Exercise 17: Phase Shifting of Coils

Switch-on and switch-off behavior of coils

Objective:

We will see how **current lags behind the voltage** with the scope. This may look exactly like the capacitor activity but you will notice the measuring points are the same but the channels appear to have swapped. **This behavior is also known as phase shifting except now the current lags behind the voltage by 90°.**

In the second part of this exercise we will change our input to a sine wave and experiment with changing the frequency of the input, at some point we should see an attenuation of the signal across the coil. *Attenuation is a general term that refers to any reduction in the strength of a signal.*

As instructed by your trainer, construct the circuit shown in Figure 01-60 for a coil to represent the voltage-current relationship:

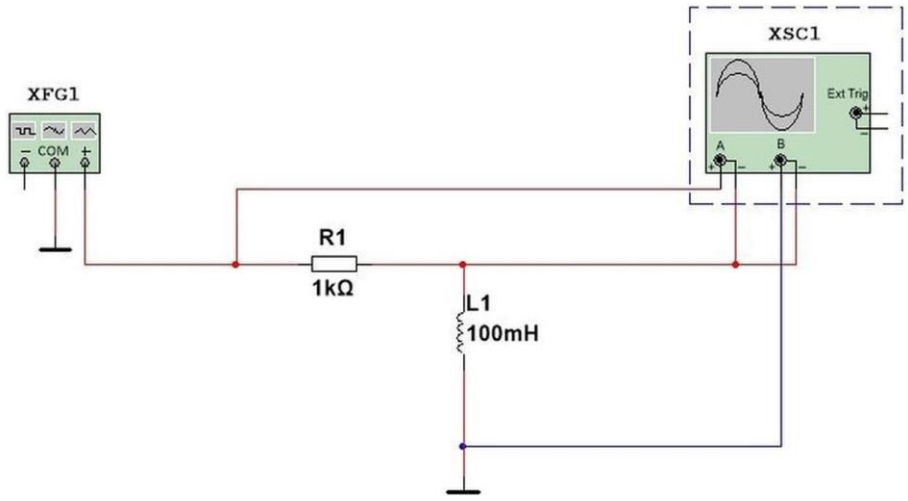


Figure 01-60 – Circuit diagram: Switch-on and switch-off behavior of a coil

GTT_010781

Devices used:

- UniTrain I
- Resistance R_1 = 1 kΩ
- Coil L_1 = 100 mH

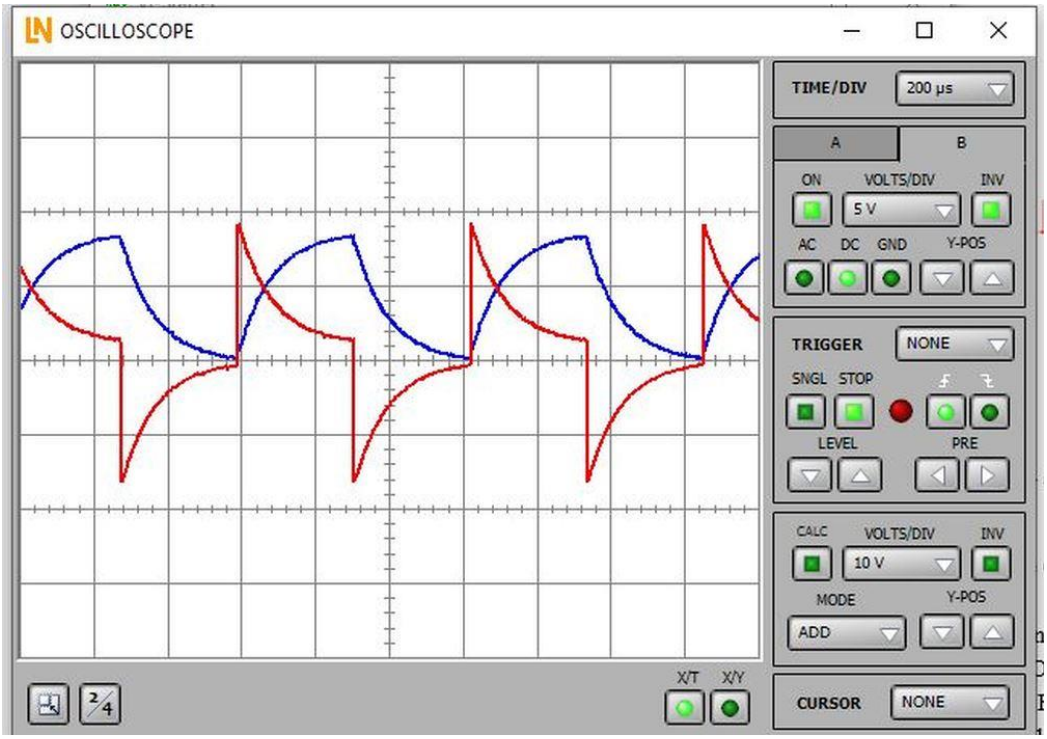
Function generator

- U = 10 V
- f = 1.6 kHz

Oscilloscope settings:

- DC range
- Channel A 5 V/div
- Channel B 5 V/div
- Time base 200 µs/div

In the experimental setup, a time shift of the current and voltage of the coil can be seen on both channels. The current lags behind the voltage by 90 degrees. This effect is called phase shifting, where coils behave in the opposite way to capacitors.



What do you notice about the signals?

Now adjust the frequency and see the response in the circuit that the coil impacts, especially as the frequency goes higher and higher.

Note your findings below:

11 Day 2 Review

When performing manual insulation resistance measurements in a HV system, what point do you measure between and what is the specification? Where should you never test between?

Which factors primarily influence the inductance of a coil?

Which factors primarily influence the capacitance of a capacitor?

Equipotential bonding is a measure of what? (What does it protect against)

How does a capacitor behave in an AC circuit? DC circuit?

Which document describes measurements and values for insulation monitoring? What are the limit values?

12 Bridge Circuit

The bridge circuit is also called an H-circuit, H-bridge or full bridge. It is an electrical circuit in which five components are connected together in the basic form in the shape of the uppercase letter H. The cross connection is called a bridge branch.

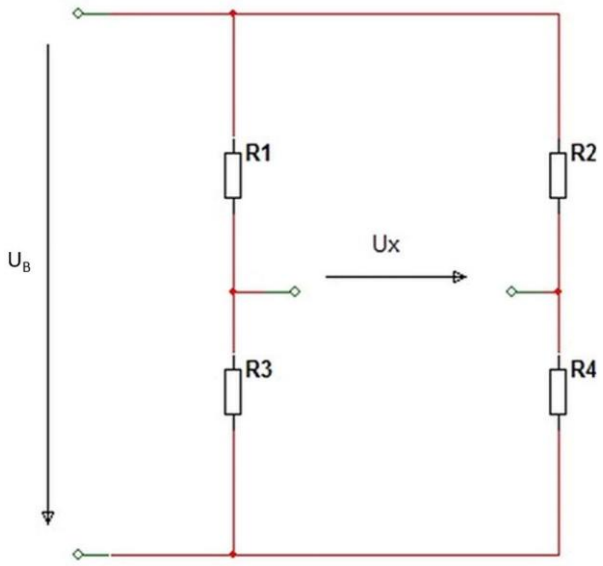


Figure 01-79 – Bridge circuit where U_B = Operating voltage

GTT_010799

If a bridge circuit consists of resistors, it can be interpreted as a parallel connection of two voltage dividers. This design has the advantage over a single voltage divider that the voltage and current in the bridge branch can be changed not only in magnitude but also in polarity. This is done by adjusting the resistors.

Bridge circuits can have the following variants:

- Quarter bridge with one variable resistor
- Half bridge with two variable resistors
- Full bridge with four variable resistors

Bridge circuits are used in measurement technology. The measuring object is part of the voltage divider of one side. At least one further part is variable to be able to carry out a zero adjustment in the bridge branch. The measuring instrument in the bridge branch can distinguish between negative and positive values.

The voltage U_x is tapped between the parallel circuit on the bridge branch. Under the condition that:

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

The voltage U_x = 0 V. This balances the bridge circuit. To measure ohmic resistances, a direct voltage can be applied to the measuring bridge. To measure impedances of coils or capacitors, operation with alternating voltage is necessary.

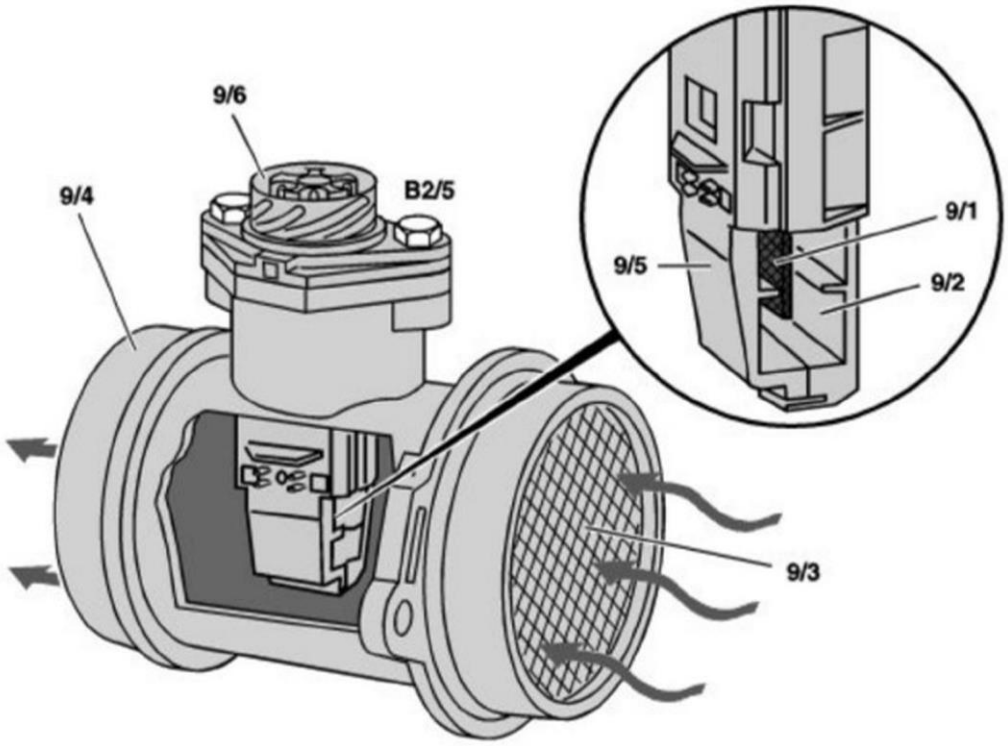


Figure 01-80 – Mass air flow sensor

GTT_010800

If, for example, a resistor is replaced by a resistor that changes its resistance value depending on the temperature, the temperature change is represented by the voltage U_x. This voltage is fed to further electronics and processed.

Bridge circuits are used to measure e.g.

- Pressure
- Temperature
- Flow volume
- Expansion of metals
- Torsion of metals
- Tensile load of metals
- Lights

The circuit is also known as Wheatstone's measuring bridge.

12.1 Exercise 18: Wheatstone Bridge Calculation

Objective:

In this exercise we will build a Quarter bridge with one variable resistor, as we know from previous pages, there are several other variations of bridge circuits. We will use ohm's law and Kirchhoff's rules to calculate current in circuit I1 (our fixed side of the bridge) and then calculate the other side of the bridge for two end stops of a variable resistor in the second branch I2. In addition, we will determine the voltage difference at U_X thus comparing a constant known side of the bridge to the variable side of the bridge.

Together with the trainer, calculate the voltage on the bridge branch of the Wheatstone measuring bridge (see Figure 01-81) and document this calculation in your documents.

A potentiometer is used for resistor R_4, which has the end stops 0 Ω (100 %) and 10 kΩ (0 %)

To make our calculations as accurate as possible we will measure the resistance of the potentiometer at both end stops.

Potentiometer at 100% (lower value) _____ at 0% (higher value) _____

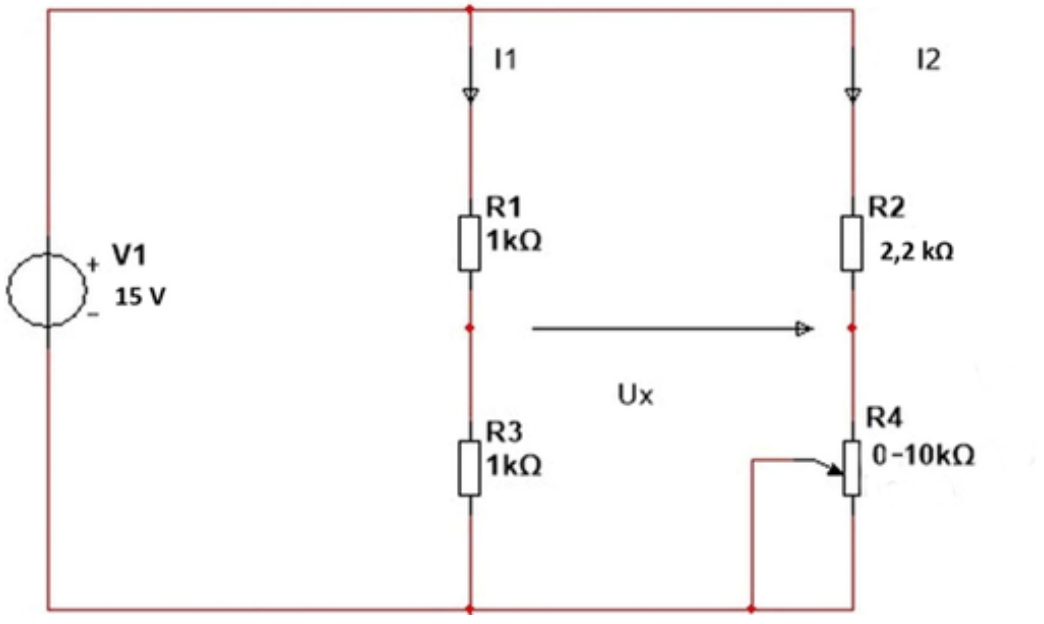


Figure 01-81 – Calculation of Wheatstone measuring bridge

GTT_010801

a) First, we need to calculate the resistance of each branch. For the calculations of the second branch you will need to measure the value of YOUR variable resistor at each of the end stops. You will have two resistance values for the second branch. One with the resistor at 0% and one with the resistor at 100%

Now, determine the current I_1 in the first branch:

b) Now we will calculate the currents in the second branch for the potentiometer at both end stops (resistor at 0% position and 100% position).

c) Using these values, find the voltage drop at each resistor and **find the value the meter (or control unit) will read at U_x** for both end stops.

To assist your calculations:

For end stop 100% use formula:

For end stop 0% use formula:

12.2 Exercise 19: Wheatstone Bridge Measurement

Objective:

In the previous exercise we did the calculations, now we can build this and test. We suggest you first check the variable resistor with an ohm meter to ensure it is working correctly and where you need to connect it within the bridge circuit. This will also serve to understand which way to turn the variable resistor to match your calculations for 0 and 100% end stops.

As instructed by the trainer, set up the Wheatstone measuring bridge calculated earlier in the UniTrain I training system according to the circuit diagram in Figure 01-82.

Measure the voltage changes in the bridge branch and document the result.

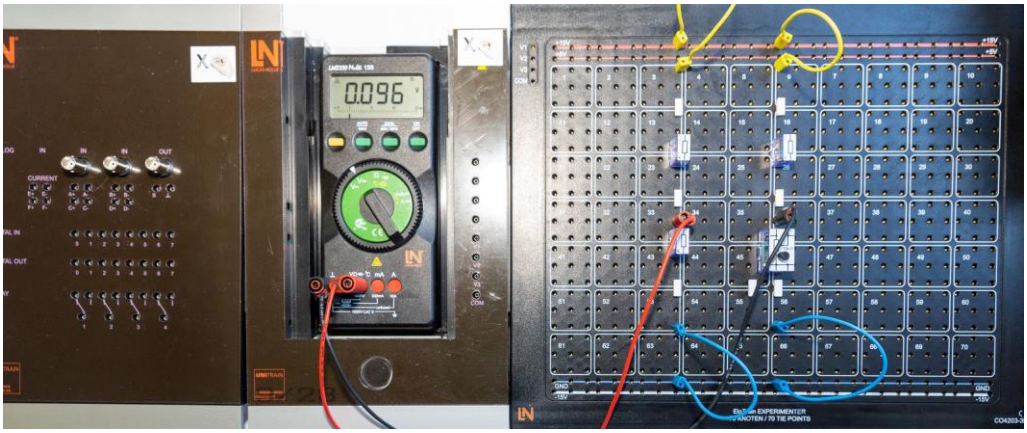


Figure 01-82 – Circuit diagram: Wheatstone measuring bridge

GTT_010803

Devices used:

- UniTrain I
- Multimeter
- Resistance R_1 = 1 kΩ
- Resistance R_2 = 2.2 kΩ
- Resistance R_3 = 1 kΩ
- Potentiometer R_4 = 0 -10 kΩ (= variable resistor, here for simulation of a sensor)
- Supply voltage = 15 V

Voltage with potentiometer at 100% _____ at 0% _____

Document results

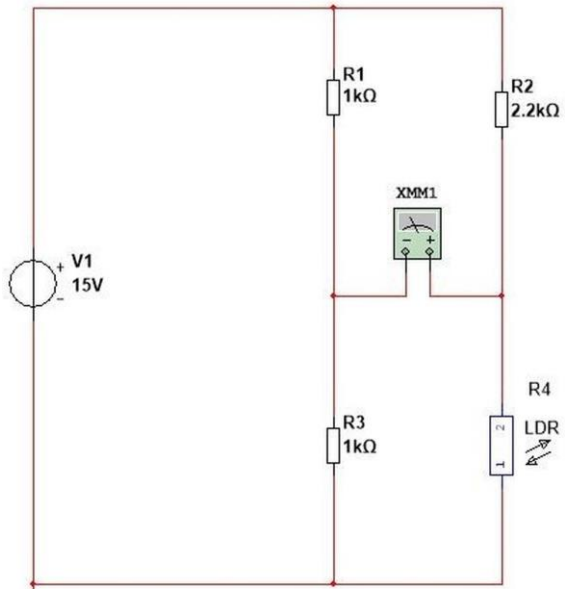
12.3 Exercise 20: Wheatstone Bridge: Illuminance (light sensor)

Objective:

Here we will replace the variable resistor that we had to manually adjust with an LDR. We can then perform some measurements with a voltmeter at U_X (across the bridge) and simulate for example a light sensor to turn on-off the vehicle's lights depending on light conditions.

LDR Values: Light - _____ Dark - _____

To measure the illuminance, a photoresistor (Light Dependent Resistor, LDR) is inserted into the previously constructed circuit instead of the potentiometer and the voltage change on the bridge branch is observed under different lighting conditions.



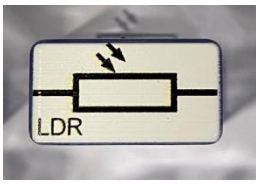


Figure 01-84 – Wheatstone measuring bridge with LDR GTT_010804

Figure 01-85 – Setup of Wheatstone bridge for illuminance measurement

GTT_010805

Devices used:

- UniTrain I
- Multimeter
- Resistance R_1 = 1 kΩ
- Resistance R_2 = 2.2 kΩ
- Resistance R_3 = 1 kΩ
- LDR (Light Dependent Resistor, approx. 60 kΩ)
- Supply voltage = 15 V

Using the same formulas from the previous exercise**, calculate the voltage at Ux** with the LDR in two states, with light and in the dark. Then prove your calculations by measuring at Ux in your circuit.

13 Signal technology

13.1 Inversion

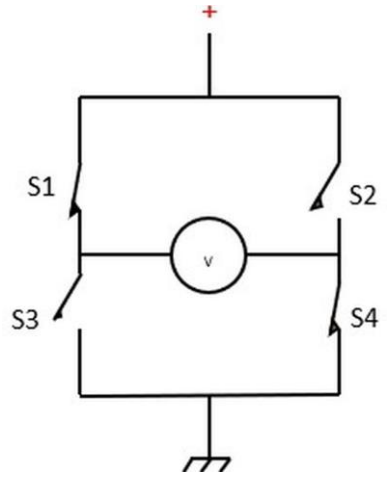


Figure 03-01 – H-bridge

GTT_010836

V	Consumer
S1- S4	Switches 1 - 4

For bidirectional operation of a motor, the direction of current through the motor must be changed. A control system with the aid of four switches is used for this purpose.

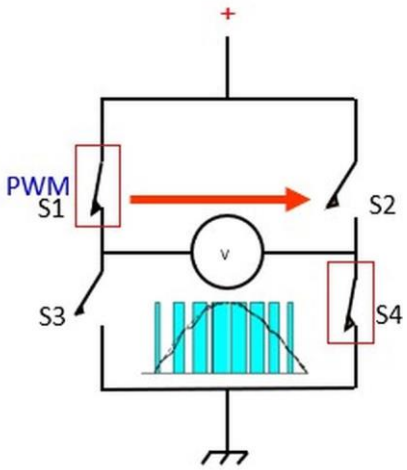


Figure 03-02 – H-bridge clockwise rotation

GTT_010837

V	Consumer
S1- S4	Switches 1 - 4

For clockwise rotation, switches S_1 and S_4 must be closed. The current now flows from + via S_1 to the motor. From the motor it flows via S_4 back to the voltage source.

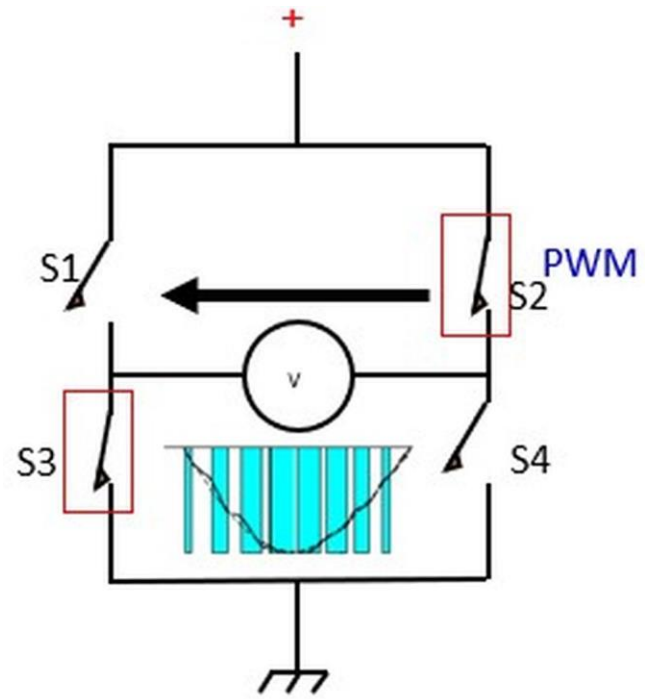


Figure 03-03 – H-bridge counterclockwise rotation

GTT_010838

V	Consumer
S1- S4	Switches 1 - 4

To reverse the direction of rotation, switches S_2 and S_3 must now be closed. The current now flows from + via S_3 to the motor and via S_2 back to the voltage source. In an electronic control system, the switches, shown symbolically here, are replaced by transistors.

Use in automotive engineering:

- Power output stage of an inverter in high-voltage technology
- Electric power steering

13.2 Exercise 21: Simulating change of rotation of DC machines by means of an H-bridge

⚠CAUTION

WARNING!

Never actuate S_1 and S_3 or S_2 and S_4 simultaneously.

- Risk of short circuit

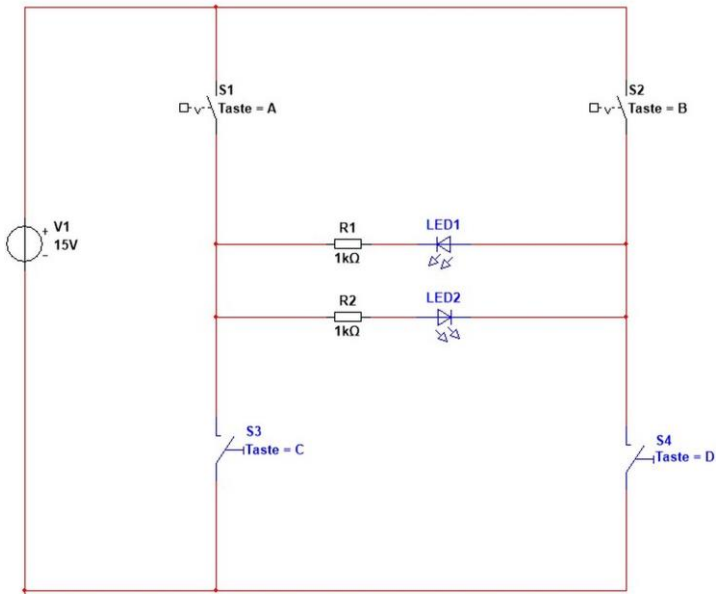
Objective:

Here we will build an H-bridge circuit with four switches and two LED's and via the switch combinations we can illuminate each LED in turn even though one is in reverse installation position showing we can switch current flow via switches. We also learn that the switch sequence is really important as the wrong selection essentially is a dead short and high current will flow potentially causing damage.

Further more we will measure the current through the two LED bridge circuits and compare these to see if there is a difference.

We will then adjust our circuit to remove the LED's and insert an electric motor where we will observe the motor direction change as we correctly operate the 4 switches. Then we will measure the current draw through the circuit when the motor is turning clockwise and then counter-clockwise (the motor has a small disc on one end that can indicate visually the direction of rotation). We can discuss the results of the current measurement compared to the LED circuit earlier.

On the instruction of the trainer, build an H-bridge with four switch's, which is used to reverse the direction of current, e.g. for motors, according to the circuit diagram 03-04. First use the LEDs connected in parallel in the opposite direction to the H-bridge. Then replace the LEDs with an electric motor. Add your knowledge of the circuit functions for both setups to your documents.



Use the following devices:

- UniTrain I
- Virtual instruments
- 2 switches
- 2 pushbutton switches
- 2 resistors of 1 kΩ each
- 2 LEDs
- 15 V power supply
- S_1 and S_2 = Locking push-button switch
- S_3 and S_4 = Pushbutton switch

a) Close the electric circuit by actuating switches S_1 and S_4 or switches S_2 and S_3.
NEVER S_1 with S_3 or S_2 with S_4 as short circuit with no load!!

Observe the behavior of the LEDs while doing so**. Measure the currents through LED_1 and LED_2 using the virtual instruments (dual amperemeter)**. You can also use the DVOM 13S.

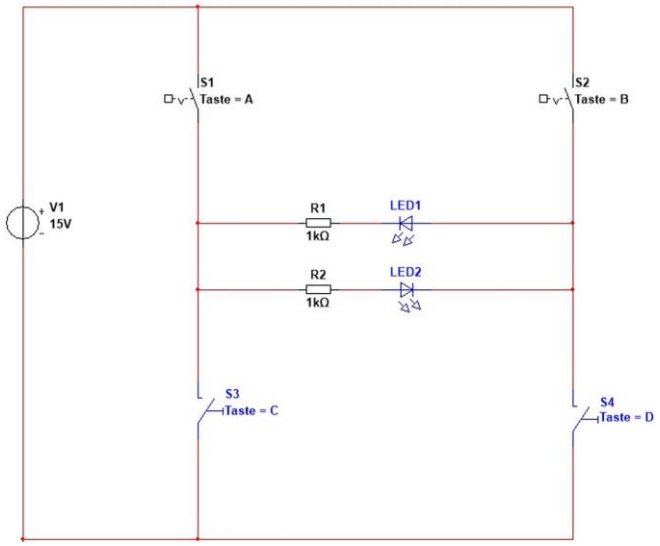


Figure 03-04 – Circuit diagram: H-bridge with 2 LEDs

GTT_010839

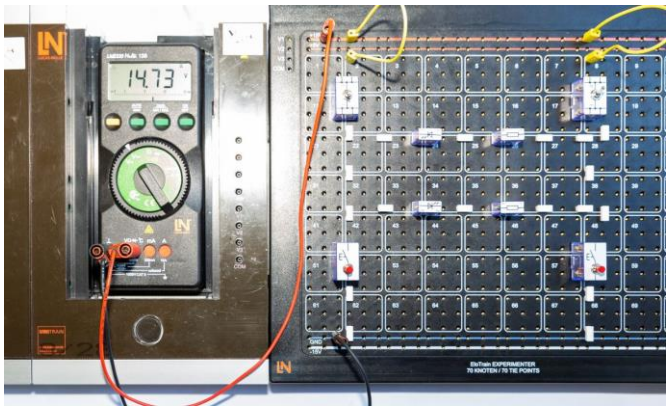


Figure 03-05 – Design: H-bridge with 2 LEDs

GTT_010840

Document your results here:

b) Now replace both LEDs with the PS2124-3M DC motor as instructed by the trainer (Figure 03-09).

Now measure the current that occurs when running clockwise and counterclockwise and document the results. Then discuss the reaction with the trainer.

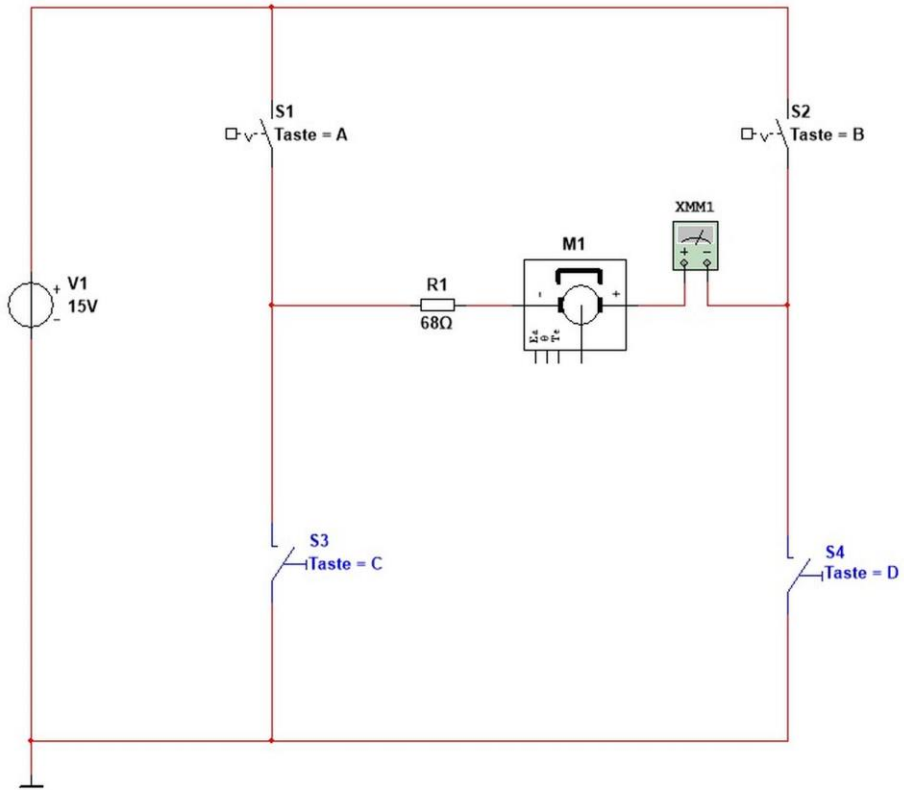


Figure 03-09 – Circuit diagram: H-bridge electric motor

GTT_010844

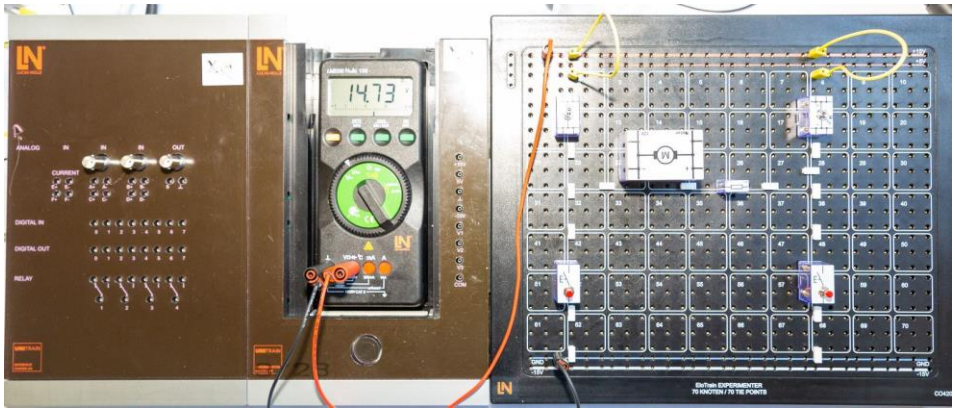


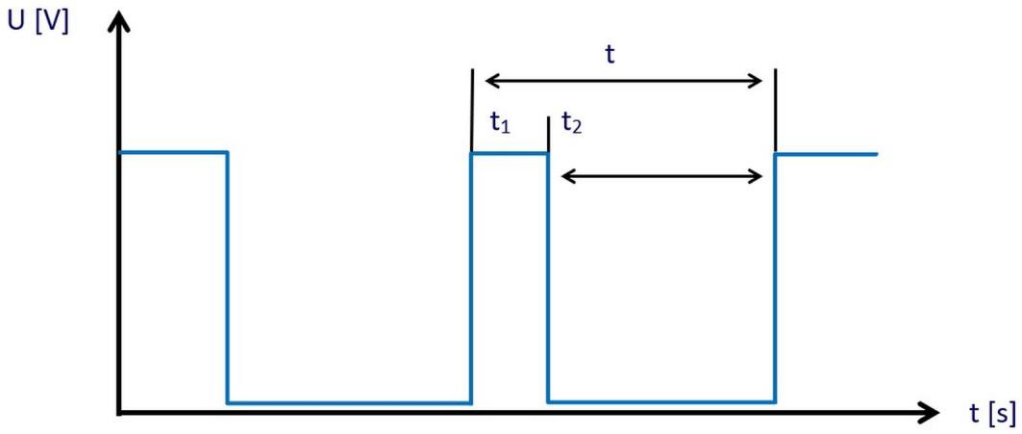
Figure 03-10 – Design: H-bridge electric motor

GTT_010845

Document your results here:

13.3 PWM signal

Pulse width modulation varies the on and off time of a square wave signal at a fixed basic frequency, i.e. it represents a time-controlled switching on and off or a switching between two different voltage levels.



Square wave signal with constant frequency where $T_1 = T_{on}$ and $T_2 = T_{off}$

GTT_011498

t = Period (total of ON & OFF time - aka pulse + pause)

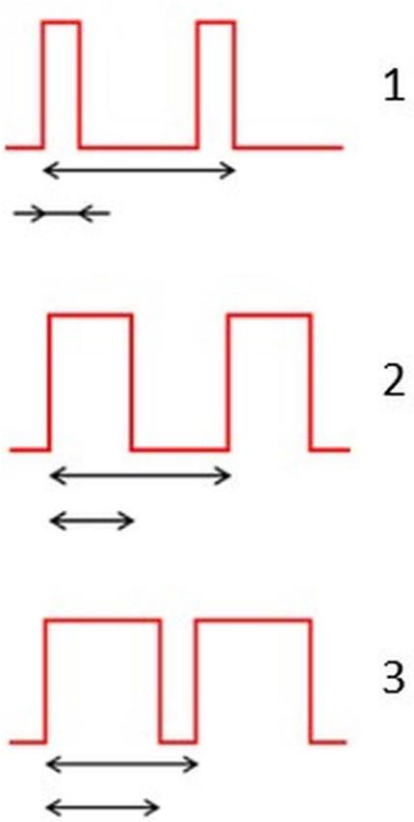
t1 = ON time (PULSE)

t2 = OFF time (PAUSE)

PWM = Ratio of pulse to period

This ratio is referred to as the duty cycle. The duty cycle is usually given as a percentage.

A short operating time leads to a low duty cycle, which results in a low average effect overall. A medium operating time results in a medium duty cycle with a medium effect. Finally, a long operating time results in a high duty cycle with a high average effect. The frequency always remains constant.



Different duty cycles

GTT_011499

1	Short	**3**	Long
2	Medium		

Pulse width modulation is therefore nothing more than a fast switch-on and switch-off process. If we explain this using the example of a light-emitting diode, we could assume that the LED would flicker. With a sufficiently high carrier frequency, the inertia of the eyes is overcome, and the LED appears darker as the duty cycle decreases. To determine the voltage, one calculates the average value over time.

PWM signals are typically used for:

- Controlling output of a PTC heater
- For lighting control
- For load control of a three-phase motor (but not speed)

Application areas of the PWM signal

Discuss with the trainer possible applications of the PWM signal in automotive engineering.

Document your results.

13.4 Exercise 22: PWM light control

Objective:

Here you will create a simple circuit and via a manually operated switch operate a LED light by regular operation of the switch. You can reproduce the pulse to period yourself to understand a PWM signal this way.

Following this understanding we can replace the switch with the signal generator function of the UniTrain equipment and adjust the ratio of pulse to period as an on-off ratio and we can also change the speed of the period by adjusting the frequency of the period.

Build a PWM-controlled circuit as instructed by your trainer according to circuit diagram 03-16. To generate a PWM signal, first use a pushbutton switch to generate the signal manually. The signal controls the LED included in the circuit. In the next step, you will exchange the pushbutton switch for a PWM generator, as instructed by the trainer. You will need an LED, the 1 kΩ resistor and a PWM generator for the second step. For both test set-ups, record your findings on the circuit function in your documents.

a) You will need the following components for this:

- UniTrain I
- LED
- Pushbutton switch
- Resistance R1 = 1kΩ
- Function Generator (**DC POS**) 10V

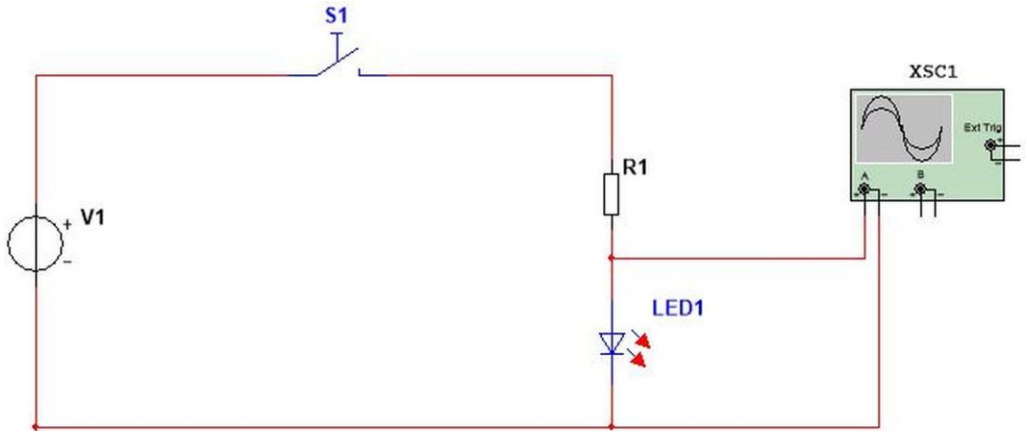


Figure 03-16 – PWM light control with pushbutton switch

GTT_010851

My observations:

b) Now exchange the pushbutton switch for the PWM generator on the instruction of the trainer (see circuit diagram 03-18). Use the following devices for this purpose:

- UniTrain I
- LED
- 1 kΩ resistor
- PWM generator

Figure 03-17 – Setup: PWM light control with PWM generator

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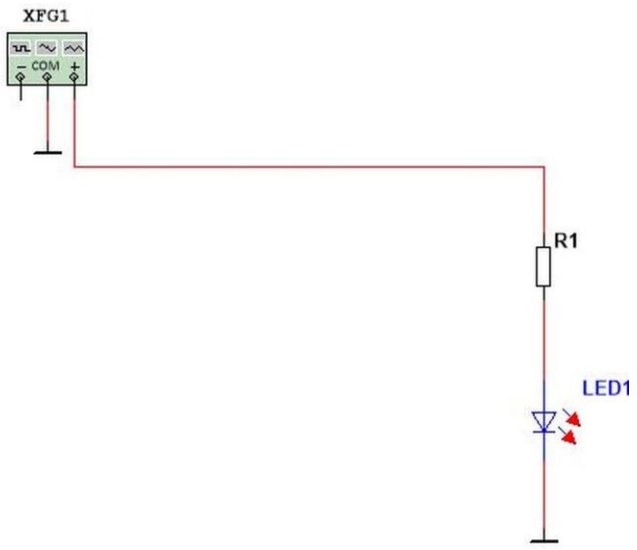

Figure 03-18 – PWM light control with PWM generator

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Make changes to the PWM and note your observations of the LED light.

My observations:

14 Diodes

Semiconductor

Semiconductors are solids whose electrical conductivity lies between that of electrical conductors and that of non-conductors. External conditions and disturbances in the structure of the atomic lattice of a semiconductor determine its conductivity. One of the most important semiconductor materials is silicon.

A chemically pure semiconductor has a lattice structure due to the atomic bonding of the individual atoms. In this process, neighboring atoms share their shell electrons to achieve a stable state. They thus form common electron pairs. If energy is added to a semiconductor, e.g. by increasing the temperature or by exposing it to light, individual electrons can break free from their bonds and move freely in the lattice compound. These free electrons are now available as charge carriers. The corresponding atom is ionized. Its electrical conductivity can be influenced by doping.

This ability gives them an importance in electrical engineering and especially in electronics. The composition of differently doped regions makes it possible to build electronic components with a direction-dependent conductivity (diode, rectifier) or a switch function (e.g. transistor, thyristor, photodiode).

14.1 Design and function

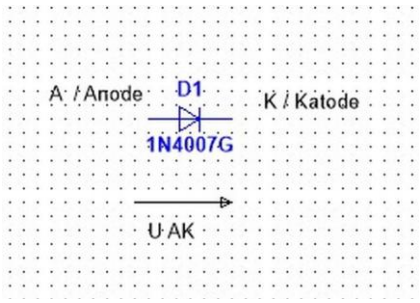

Figure 04-01 – Diode, conductive

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A diode works like a valve. In one direction the diode allows the current to pass, in the other situation it blocks the current.

When a voltage U_{AK} is applied to a diode, it becomes conductive in the forward direction. This requires a flux voltage which puts it into the conducting state.

Depending on the semiconductor material, this is:

- Germanium approx. 0.3 V
- Silicon approx. 0.7 V

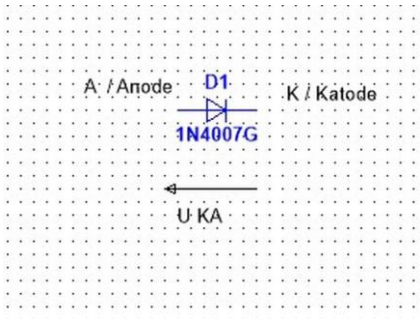

Figure 04-02 – Diode, blocking

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If the polarity of the U_{KA} voltage is reversed, the diode is blocked. It is then to be regarded as an open switch and the operating voltage drops at the diode.

Various types of diodes are used in automotive engineering:

- Rectifier diodes

  Use in circuits where high currents are rectified, e.g. in a generator or inverter.

- Small signal diodes

  Used in signal processing e.g. as rectifiers, freewheeling diodes in relays or also as voltage references.

- Z-diodes (Zener diodes)

  Use as a voltage stabilizer, since the breakdown voltage (reverse direction) can be specifically influenced with these diodes and the diode is not destroyed when this is reached.

- Optical diodes

  LEDs, laser diodes and photodiodes.

14.2 Zener diode: Design and function

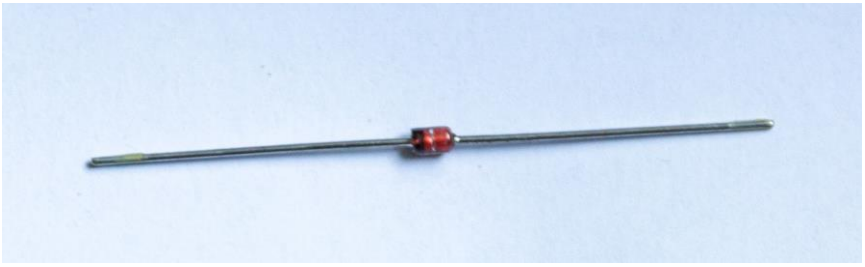

Figure 04-03 – Zener diode

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The designation of the Zener diode comes from the Zener effect discovered by C. Zener. This is understood to mean the release of electrons from the lattice bond as a result of a high electric field strength. On the housing of a Zener diode there is usually a ring on the cathode side. This marking thus corresponds to the markings of other diodes.

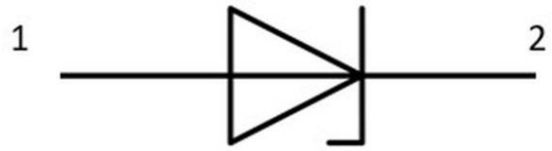

Figure 04-04 – Circuit symbol: Zener diode

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1	Cathode
2	Anode

As a rule, Zener diodes are operated in the reverse direction. In the reverse direction, a Zener diode operates up to 5 V according to the Zener effect as described above and above 5 V according to the avalanche effect.

- Zener effect

  The Zener effect describes the occurrence of a current (Zener current) in the reverse direction in a highly doped semiconductor barrier layer due to free charge carriers.

- Avalanche effect

  Electrons moved through the space charge region by an external electric field can knock the valence electrons of the Bravais lattice out of their bonds by impact ionization. They thus raise the conduction band. Sufficient external field strength gives the electrons such a large energy that, after colliding with the valence electrons, they make them available as charge carriers.

Zener diodes are primarily used for voltage regulation and protection in electric circuits due to their ability to “limit” voltage in the reverse direction instead of blocking it like a typical diode. The number given with the diode is the Zener (breakdown) voltage which specifies the voltage that is blocked by the diode in the reverse direction.

Zener diodes are available in many voltage breakdown levels. Within the Lucas-Nulle equipment we have a 6.2 V version as we can see from the model number.

Lucas-Nulle also offers: ZPD 3.3, ZPD 3.9, ZPD 4.7, ZPD 10, ZPD 12

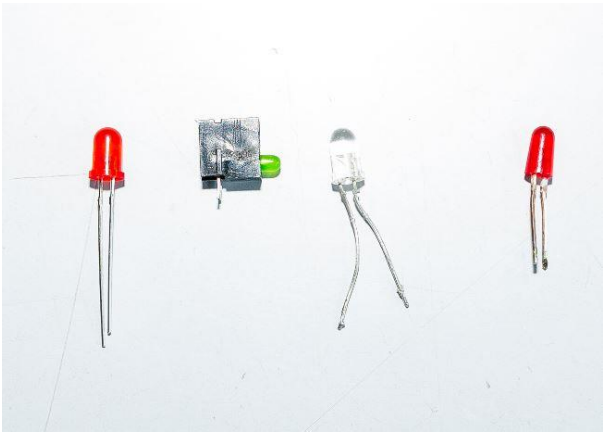
Here is an example from ‘All about circuits’ website:

Common Zener diode voltages

0.5W						
2.7V	3.0V	3.3V	3.6V	3.9V	4.3V	4.7V
5.1V	5.6V	6.2V	6.8V	7.5V	8.2V	9.1V
10V	11V	12V	13V	15V	16V	18V
20V	24V	27V	30V			
1.3W						
4.7V	5.1V	5.6V	6.2V	6.8V	7.5V	8.2V
9.1V	10V	11V	12V	13V	15V	16V
18V	20V	22V	24V	27V	30V	33V
36V	39V	43V	47V	51V	56V	62V
68V	75V	100V	200V			

1) If the circuit has a 12V supply and a 5.5 Zener Diode, how much voltage will be present after the diode?

14.3 Light-emitting diode: Design and function



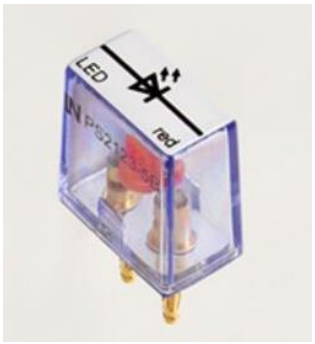


Figure 04-05 – Zener diode

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Positive voltage U_{AK} at LED lamps

Different colors mean different flux voltages.

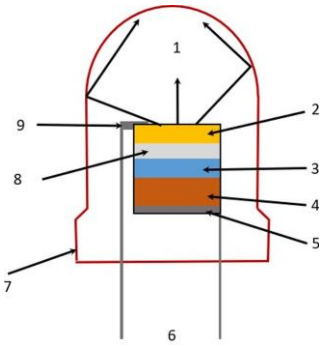

Figure 04-06 – Design: LED

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1	Emitted light	**6**	Connections
2	p-zone	**7**	Transparent plastic housing
3	n-zone	**8**	Active material
4	Substrate	**9**	Cathode
5	Anode		

Functional principle:

- p-doped and n-doped semiconductor layers
- “Holes” in the p-layer (missing electrons)
- n-layer overdoped

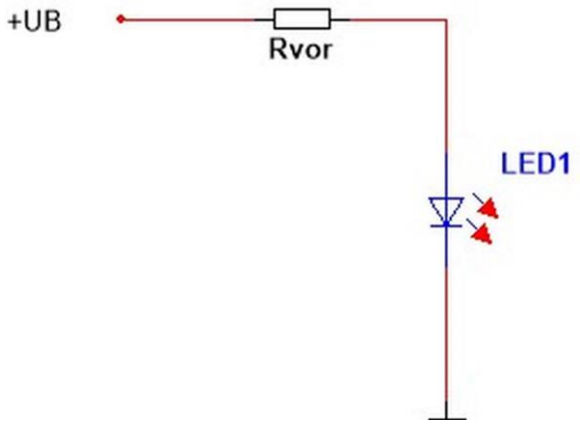

Figure 04-07 – LED; series resistor Rvor = Resistor before
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Above a certain voltage, the n-electrons cross the barrier between p and n. This releases electromagnetic energy and thus photons (“light particles”). **A diode always consists of several layers of semiconducting material. This material determines the wavelength and thus the color of the emitted light**. The wavelength range is very narrow, extending from the near infrared range to the visible light range. Different LED arrangements or the addition of fluorescent substances can produce mixed colors.

As a rule, light-emitting diodes are long-lasting. However, there are some factors that can shorten the life of light-emitting diodes. The most important factor is temperature; too high a temperature has a negative impact on service life. Therefore, a functioning heat management system is especially important for light-emitting diodes. Sufficient heat dissipation is usually achieved via a heat sink.

This is a mostly metallic or ceramic body on the diode that ensures adequate dissipation of the heat generated. In household lamps, the heat sinks are often integrated into the housing and are not perceptible as such by the layperson.

Another way to reduce heat is to reduce current flow, but this results in a reduction in brightness.

Humidity and certain chemical influences such as smog or salt water air also have a negative impact on the service life of light-emitting diodes.

Basically, the cooler the environment of a light-emitting diode (be it through good heat management or a low ambient temperature), the more efficiently the system works and the longer the lifetime.

The following formula can be used as a rule of thumb for the standard LED:

$$R_{vor} = \frac{U_B - UD}{I_D}$$

U_B = Voltage supply

UD = Voltage drop of LED

I_D = Current through diode

Whenever using an LED, make sure to always have a resistor! The resistor limits the current, which will keep the LED from burning out!

The permissible diode current can usually be found in the product data sheet.

Electrical / Optical Characteristics at TA=25°C

Symbol	Parameter	Device	Typ.	Max.	Units	Test Conditions
λpeak	Peak Wavelength	Super Bright Red	660		nm	IF=20mA
λD [1]	Dominant Wavelength	Super Bright Red	640		nm	IF=20mA
Δλ1/2	Spectral Line Half-width	Super Bright Red	20		nm	IF=20mA
C	Capacitance	Super Bright Red	45		pF	VF=0V;f=1MHz
VF [2]	Forward Voltage	Super Bright Red	1.85	2.5	V	IF=20mA
IR	Reverse Current	Super Bright Red		10	uA	VR = 5V

Notes:
1.Wavelength: +/-1nm.
2. Forward Voltage: +/-0.1V.

In the above specification sheet we see LED forward voltage is 1.85 V typical (2.5 V max.) & we also see current forward (I_F) as 20mA.

Below we can see another example of luminosity that can be achieved with different current flow from Normalhell (normal bright) to Superhell (super bright).

Figure 04-08 – LED: Luminosity

For practice you can use the prior information to determine the Rvor for the LED in the specification sheet abstract.

U_B = 15 V DC

UD = 2 V DC

I_D = 20mA

$$R_{vor} = \frac{U_B - UD}{I_D}$$

14.4 Exercise 23: Forward and reverse behavior of a diode

Objective:

Here you will create a simple circuit to demonstrate the forward and reverse behavior of a diode. First, we use a rectangle signal, which has pulses in positive and negative voltages and we will see that the diode only allows a 'forward' pass through of the current and not a reverse current. Then we can switch to a sine wave and repeat the experiment and see the effects using what we typically refer to as AC. We can also apply Kirchhoff's second law in a calculation bearing in mind the voltage values you use may be peak or RMS.

Using the UniTrain I training system, build a circuit as shown in Figure 04-09 on the instructions of the trainer. The circuit is used to demonstrate the forward and reverse behavior of a diode.

Document your results and discuss the voltage curves with the whole class afterwards.

First generate a rectangle-wave alternating voltage with an amplitude of 10 V and a frequency of 100 Hz with the function generator. Use the oscilloscope to visualize the voltage that drops across the diode.

In the next step, generate a sinusoidal alternating voltage of the same frequency and amplitude.

Use the following components and settings for this purpose:

- UniTrain I
- Function generator
  - Amplitude voltage U = 10 V
  - f = 100 Hz
  - Rectangle wave voltage
- Dual-channel oscilloscope
  - D/C range
  - Channel A 5 V/div
  - Channel B 5 V/div
  - Time base 5 ms/div
- Resistance R_1 = 1 kΩ
- Diode D_1

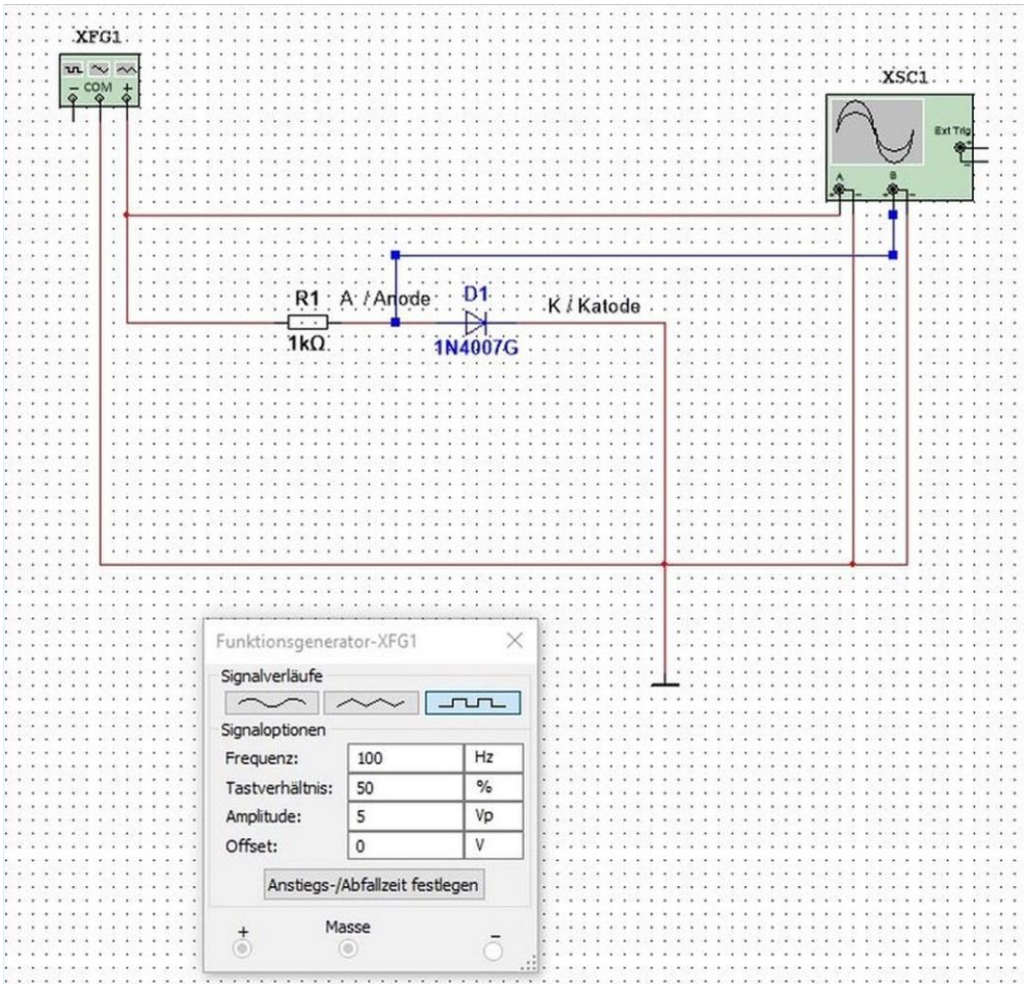

Figure 04-09 – Circuit diagram: Forward and reverse behavior of a diode

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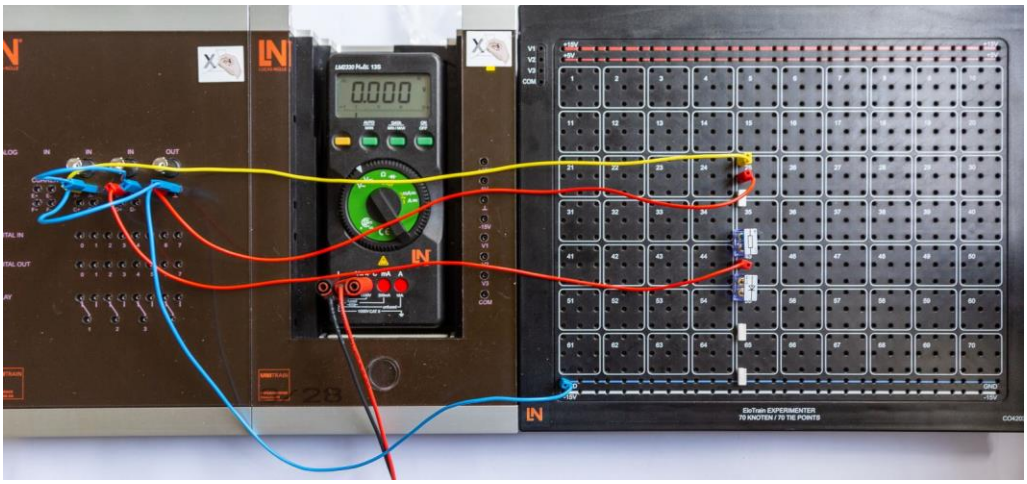

Figure 04-10 – Setup: Forward and reverse behavior of a diode

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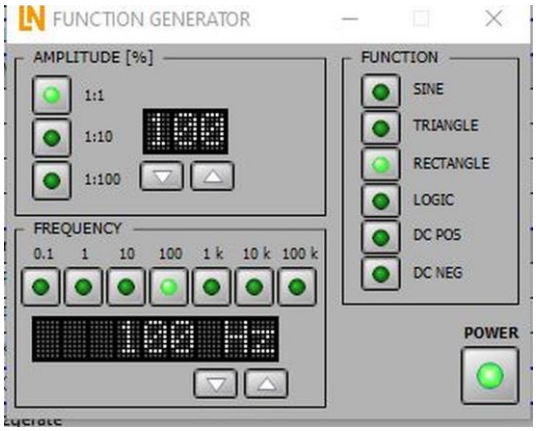

Figure 04-11 – Function generator settings

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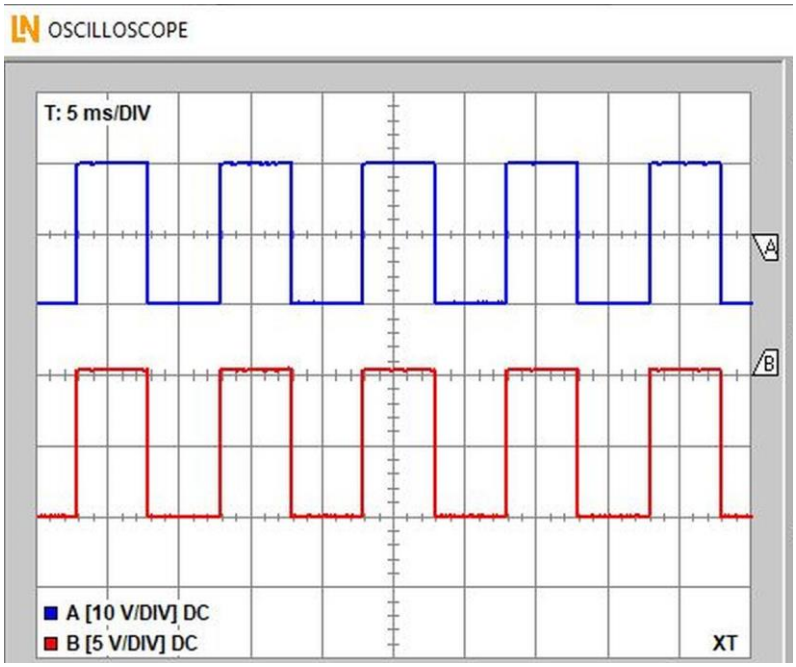

Figure 04-12 – Oscilloscope settings, note the 0-line for each channel

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DISPLAY OF OSCILLOSCOPE

Channel A: Input voltage

Channel B: Voltage curve at the diode

The square wave function of the function generator periodically switches the input voltage on and off. At the positive half-wave, the diode is switched in the forward direction. The voltage curve of the flux voltage at the diode is visualized on channel B. At the negative half-wave, the complete voltage drops at the diode. Using a sine wave we see the same result, except we see the sine wave pattern instead.

The figure below shows the voltage waveforms of a function generator when using the “Sine” setting:

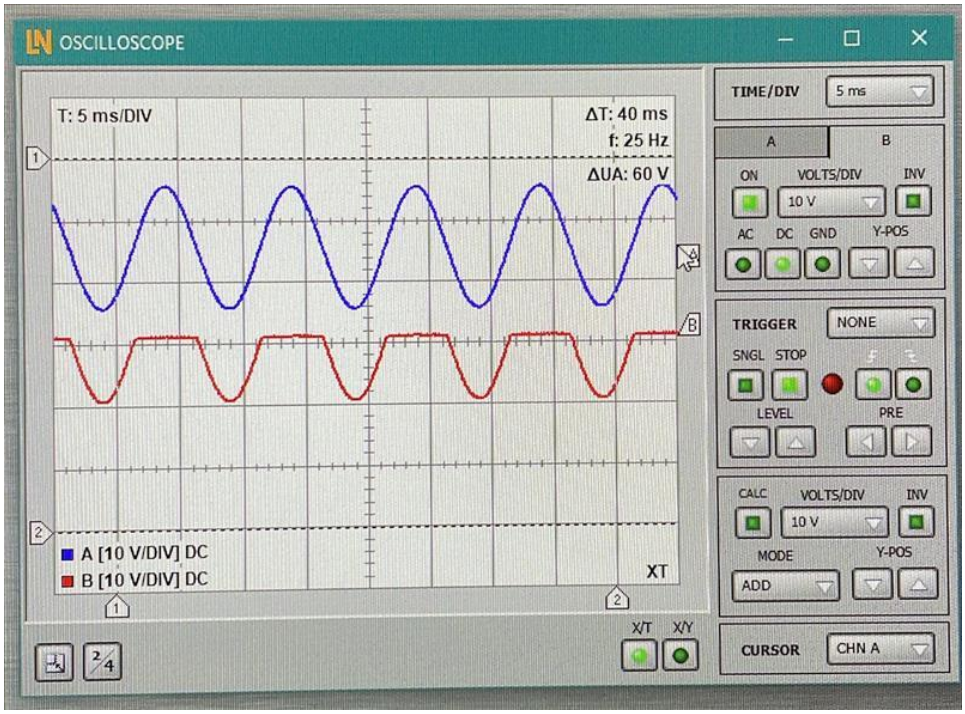


Figure 04-13 – Measurement: Forward and reverse behavior of a diode, again note the ‘0’ line for each channel.

GTT_010866

Document the results of your measurements here:

Kirchhoff's second law can be proved here:

$U_{Input} - U_R - U_D = 0$

To calculate, first measure U_R (voltage drop across resistor R_1) _____

Second, measure U_D (voltage drop across diode U_D) _____

Then using the voltage input U_{INPUT}, prove Kirchhoff's law.

14.5 Exercise 24: Diode test

⚠CAUTION

Application of a voltage.

Destruction of component or measuring device.

▶ Make sure that the power supply of the electric circuit is switched off and there is no voltage on the diode. There may still be voltage present in the circuit after the electric circuit is switched off due to charged capacitors. These capacitors must be discharged before testing.
To be able to test a diode, it may be necessary to remove at least one of its connections from the electric circuit.

Objective:

Here you will discover and practice two methods of checking a diode with a multimeter. Some multimeters have a special diode check function which is the preferred way to test a diode. Either way, you will try both methods and analyze the results so you are familiar with testing diodes. Sometimes with the equipment we have a diode gets damaged in an experiment, so this knowledge is key to have if an experiment does not yield the expected or calculated result. In addition the plastic cover of the diode may have been put back on in the reverse direction to the diodes forward/reverse function.

Perform tests of diodes using the multimeter and document your results.

A digital multimeter can be used to test diodes in two ways:

- Resistance mode
  Use only if a multimeter does not have a diode test mode.
- Diode test mode
  Safe procedure

a) DIODE TEST IN RESISTANCE MODE

Note that this test mode cannot provide absolute certainty about the function of a diode. This test mode can be used in addition to the diode test mode in certain applications to confirm its result.

Figure 04-14 – Diode test in resistance mode

GTT_010867

For this procedure, set the multimeter to resistance mode.

The resistance of the diode disconnected from the electric circuit is measured and the displayed measurement value is noted. The diode is then measured the other way round and this displayed measurement value is also noted. The resistance in the forward direction should be in the range of 1 kΩ to 10 MΩ for a functioning diode. A diode is defective if the measurement values for both directions are identical.

The comparison with a demonstrably functioning diode gives the qualitative statement about its condition.

Record the results of your measurements for the resistance mode here:

b) DIODE TEST MODE

Figure 04-15 – Diode test mode

GTT_010868

In diode test mode, the multimeter applies a low voltage to the diode. In the forward direction of the diode, the display shows a voltage drop. The diode test procedure is similar to the resistance mode test. The diode disconnected from the electric circuit is measured and the displayed measurement value is noted.

The diode is then measured the other way round and this displayed measurement value is also noted. A functioning diode shows the following voltage drop in forward direction:

- Silicon diodes 0.5 to 0.8 V
- Germanium diodes 0.2 to 0.3 V

With a functioning diode, the multimeter displays “OL” when measuring in the reverse direction. This means that the measurement value is outside the measuring range of the multimeter and the diode reacts practically like an open switch.

With a defective diode, there is no current flow in either direction. Thus, the multimeter shows “OL” (overload) in both directions.

If the diode has a short circuit, the same voltage drop is displayed in both directions.

1) Perform the measurements and note the measurement values for the diode test mode.

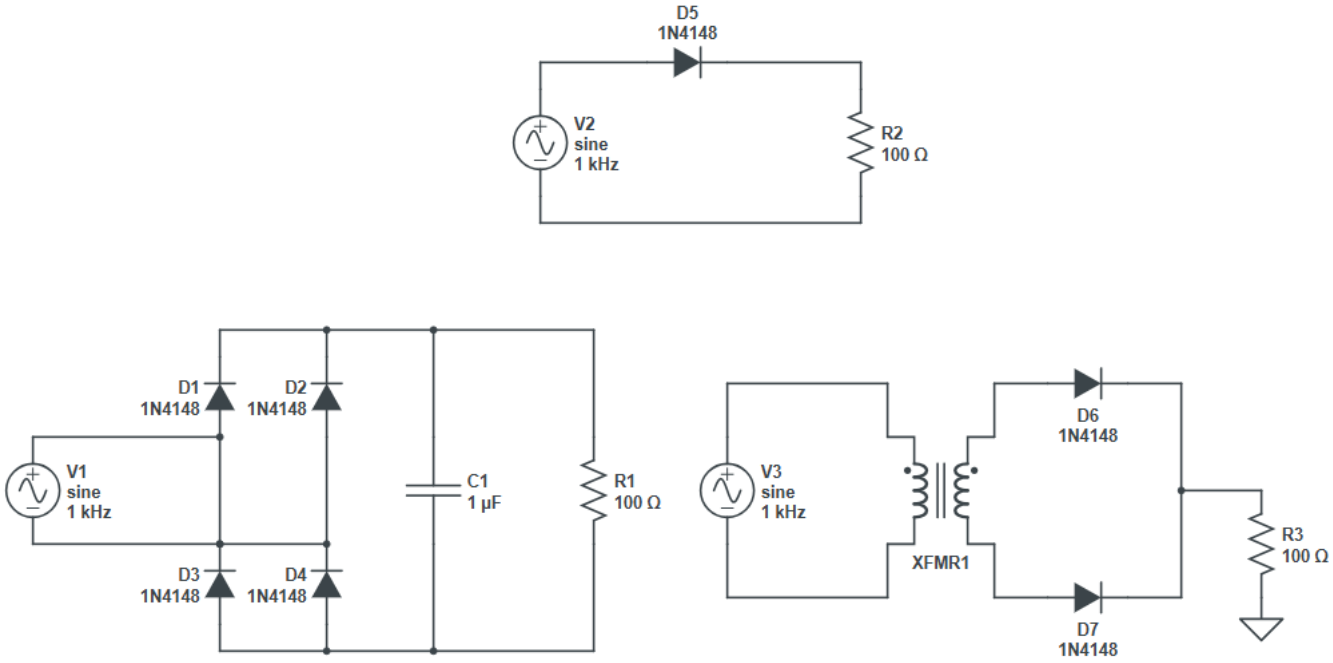
2) What kind of diode did you identify by the values and also the condition?

15 Rectifiers

Basic Types of Rectifiers

The task of a rectifier is to convert alternating voltage into direct voltage. Due to their property of allowing current to flow in one direction and blocking the other direction, diodes can be used for rectification. There are many methods to achieve this as we may recall from the eLearnings or your experiences.

Below is an image of some types of rectifiers:



Where do we use rectifiers in vehicles?

15.1 Half-wave rectification

The simplest circuit for rectifying an alternating voltage is the "half-wave rectifier circuit", which consists of a simple diode.

LN offers a GE 118 (AA113) diode that is a germanium semiconductor. At the positive half-wave of the input voltage, a forward voltage U_{AK} of 0.3 V drops across the diode. The negative half-wave of the input voltage drops completely at the diode, since the diode prevents the current flow and behaves practically like an open switch. This behavior can be observed with the help of the oscilloscope at channel B.

15.2 Exercise 25: Half-wave rectification

Objective:

Here you will build a half-wave rectifier and see how the diode handles the incoming AC and essential rectifies this to a pulsating DC with basically the same frequency as the incoming signal as only a half wave rectifier. This is the simplest of AC/DC rectification and we will build on this in further exercises to improve the rectification efficiency and 'clean' up the output.

As instructed by the trainer, use the UniTrain I training system to construct the half-wave rectifier circuit shown in Figures 04-16 and 04-17 and use the oscilloscope to measure the input voltage and the voltage that drops across the diode.

Use the following equipment.

- UniTrain I
- Virtual dual channel oscilloscope
  - Coupling = DC range
  - Channel A = 10 V/div
  - Channel B = 10 V/div
  - Time base = 5 ms/div
  - Calibration channel A = Above the center of the screen
  - Calibration channel B = Below the center of the screen
- Resistance R_1 = 1 kΩ
- Function generator
  - Sinus signal
  - Amplitude voltage 10 V
  - Frequency 100 Hz

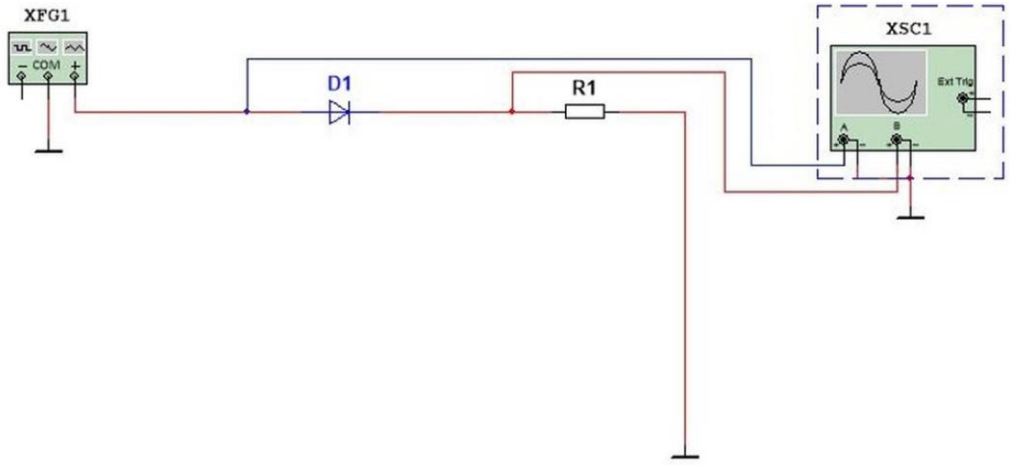


Figure 04-16 – Circuit diagram: Half-wave rectification

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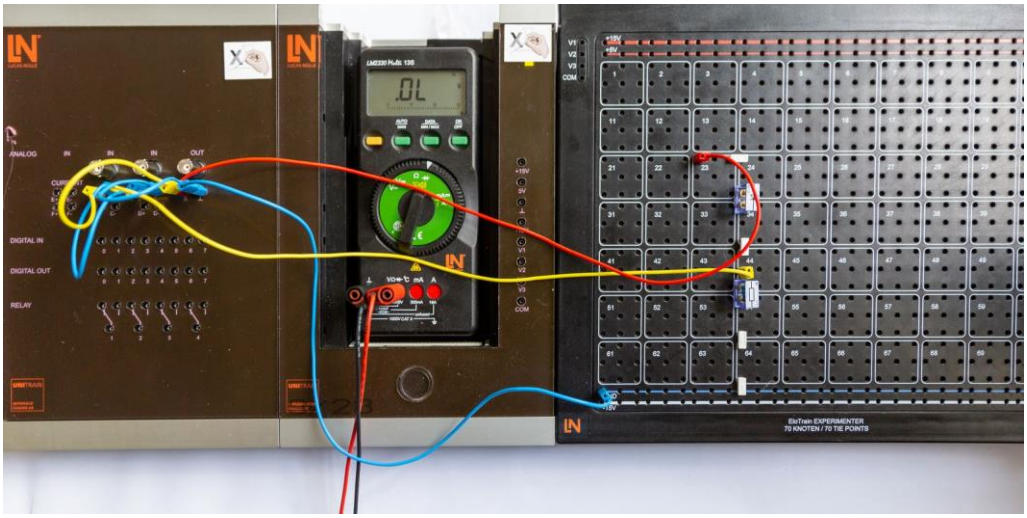

Figure 04-17 – Setup: Half-wave rectification

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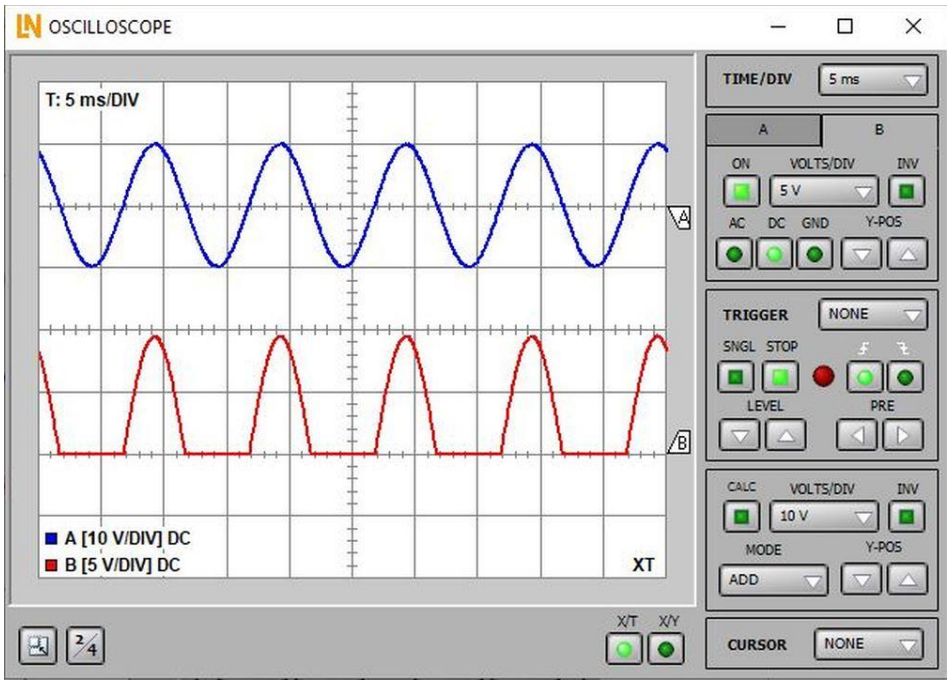

Figure 04-18 – Signal: Half-wave rectification

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Document your results here:

15.3 Rectifier bridge

Half-wave rectification has the disadvantage that the second half-wave of the alternating voltage is lost in the output voltage. In order to use the second half-wave as well, several diodes can be connected together to form a bridge circuit. Therefore, bridge circuits consisting of four diodes can be used to rectify alternating currents. This bridge circuit is also called a Graetz circuit or Graetz bridge. Graetz bridges are thus bridge-connected rectifiers in which diodes rectify the positive and negative phases of an AC signal. The result is a rectified full-wave signal.

For this purpose, two diode paths open at each half-wave of the alternating voltage and thus let the half-wave pass. If the positive half-wave is at the anode of diode D_3, then the negative half-wave is simultaneously at the cathode of diode D_2. Diode D_3 lets the current through to the further circuit when the anode is positive, diode D_2 switches the negative half-wave to ground. At the next half-wave, the positive voltage is at the anode of diode D_4, which lets the current through, and the negative voltage is at the cathode of diode D_1. This closes the electric circuit.

A full-wave current flow with double mains frequency is generated, since two diodes are always active at each half-wave.

15.4 Exercise 26: Rectifier bridge

⚠ CAUTION

Excessive voltage at the LEDs

Destruction of the LEDs

▶ The amplitude swing of 50 % must not be exceeded.

Objective:

Here you will build a rectifier bridge and see how the LEDs handle the incoming AC and essentially rectifies this to a pulsating DC with double the frequency as the incoming signal, thus taking advantage of rectifying both positive and negative sine waves of our AC input. Using LEDs allows us to visually see this function at the LEDs as well as using the virtual oscilloscope.

PLEASE pay attention to the cautions here so as not to damage the LEDs and limit current using the resistor.

As instructed by your trainer, construct the rectifier bridge shown in 04-19 and 04-21 and use the oscilloscope to measure the voltage that drops across the resistor. Then discuss the signal and the advantages and disadvantages of this circuit with the trainer and document them. Use the following devices:

- UniTrain I
- Virtual dual channel oscilloscope
- 4 LEDs
- Resistance R_1 = 1 kΩ
- Function generator
  - Sinus signal
  - Amplitude voltage = 5 V
  - Frequency = 1 Hz

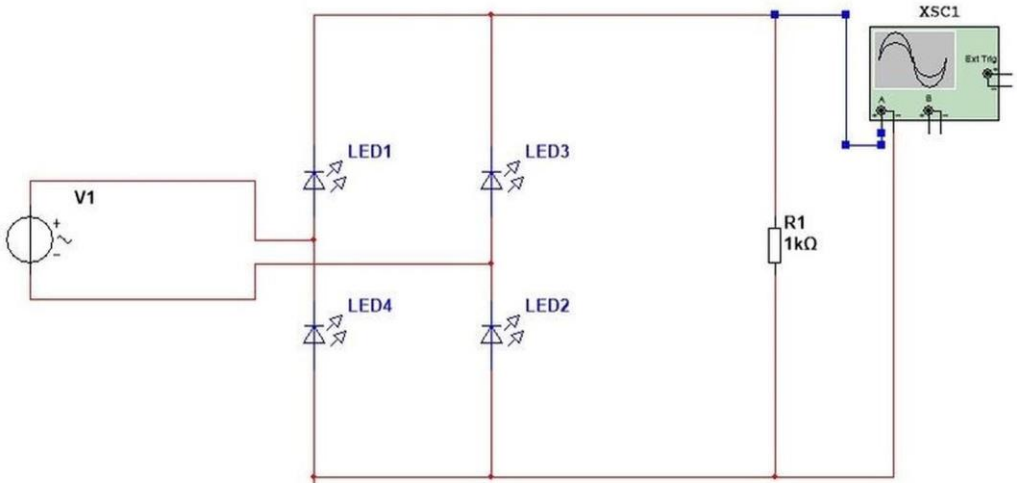

Figure 04-19 – Circuit diagram: Bridge circuit LED

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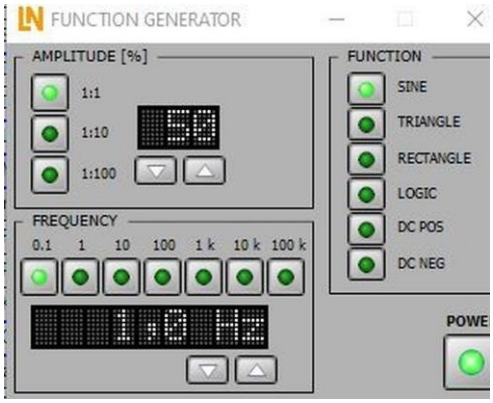

Figure 04-20 – Function generator settings

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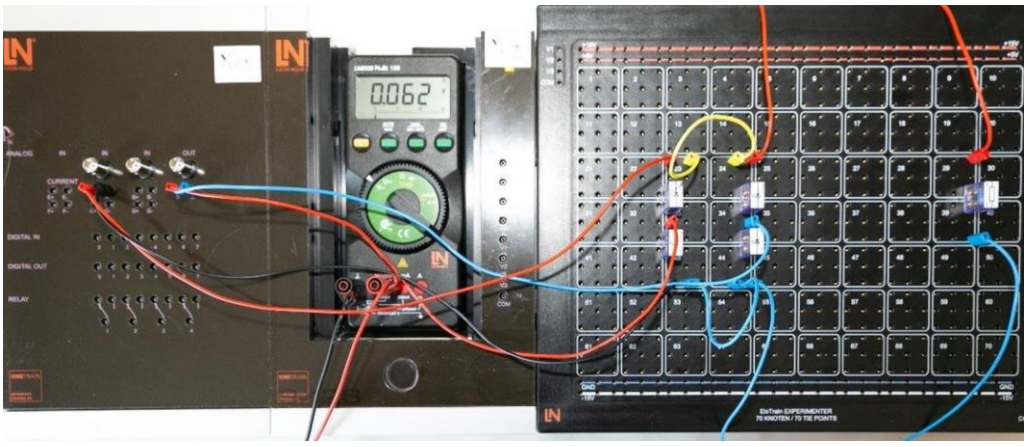


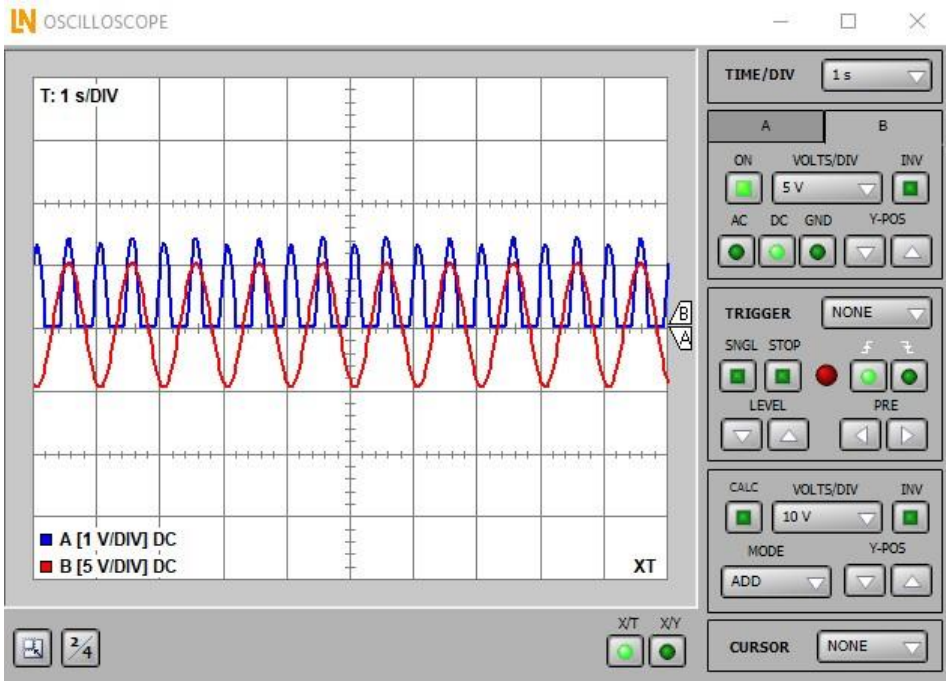
Figure 04-21 – Design: Bridge circuit LED

GTT_010874

Using this circuit, the cooperation between LED_1 and LED_2 and between LED_3 and LED_4 can be observed.

Document your results here:

Next add channel B to measure the input signal and compare the input signal to the output signal of the rectifier bridge.



Document your results here:

15.5 Exercise 27: Capacitor smoothing

Objective:

Here you will replace the LEDs with diodes and extend the bridge rectifier circuit with further components to explore methods to minimize the voltage ripple in our DC output which is a product of the rectification process.

Now, as instructed by the trainer, convert the LED bridge circuit into a rectifier bridge so that it corresponds to the setup in Figure 04-23 and 04-25 respectively. Measure it again with the oscilloscope and discuss the advantages and disadvantages with the whole class.

Use the following devices:

- UniTrain I
- Virtual dual channel oscilloscope
- 4 diodes N 4007
- Capacitor C_1 = 100 µF
- Resistance R_1 = 1 kΩ
- **Three-phase Power Source**

The voltage source of the three-phase power supply (V1,V2,V3, COM on board) has the following parameters:

- Sinus signal
- Voltage = 7.5 V RMS
- Frequency = 50 Hz

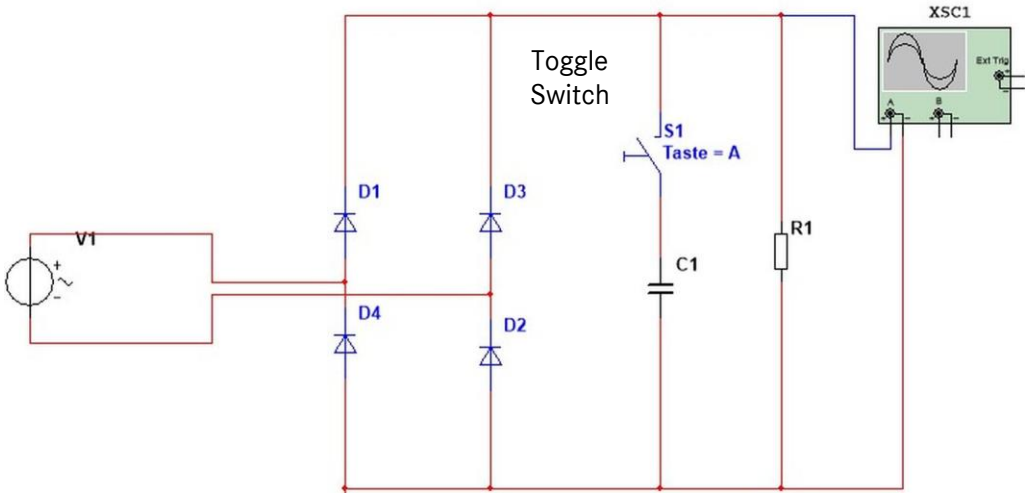
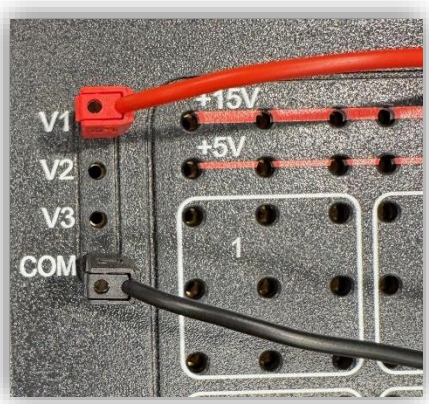
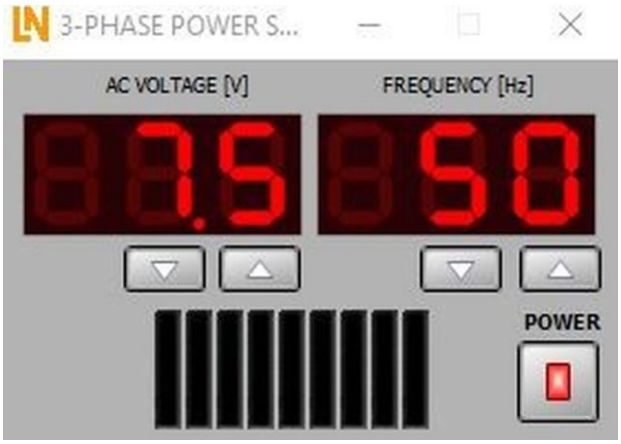


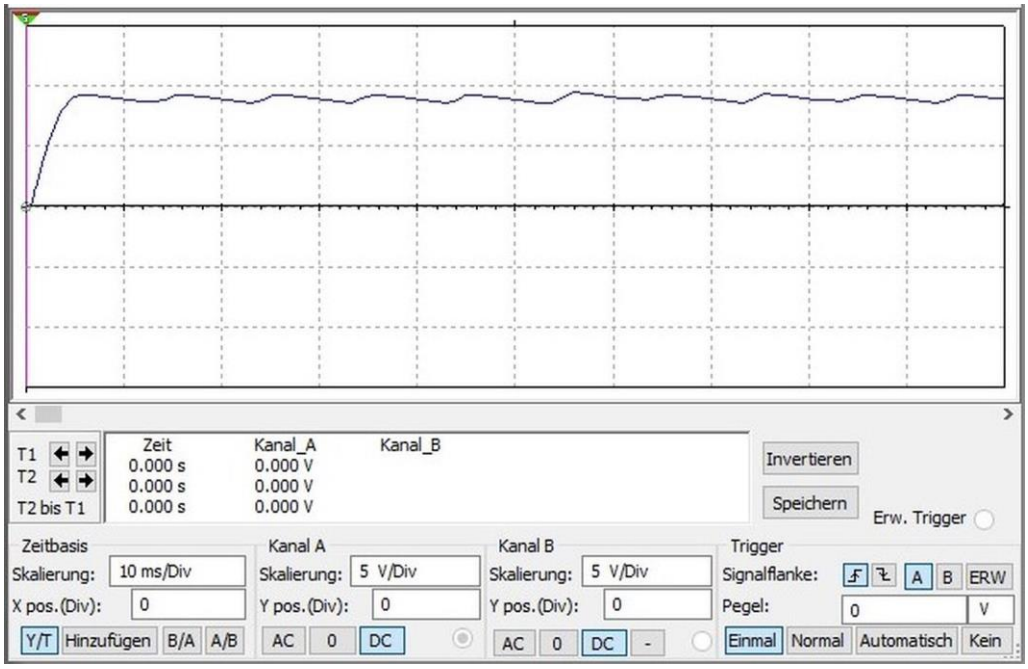
Figure 04-23 – Circuit diagram: Rectifier bridge

GTT_010876

Figure 04-25 – Design: Rectifier bridge







As we can see we have a fullwave rectifier that we can now switch on or off the capacitor via S1.

While monitoring input and output voltages switch on and off the capacitor circuit and note your observations below? You should see what is known as ripple voltage (U_{Brss}). The oscilloscope is switched to AC mode and the voltage selector switch is set to the millivolt range. The peak-to-peak value is called the ripple voltage.

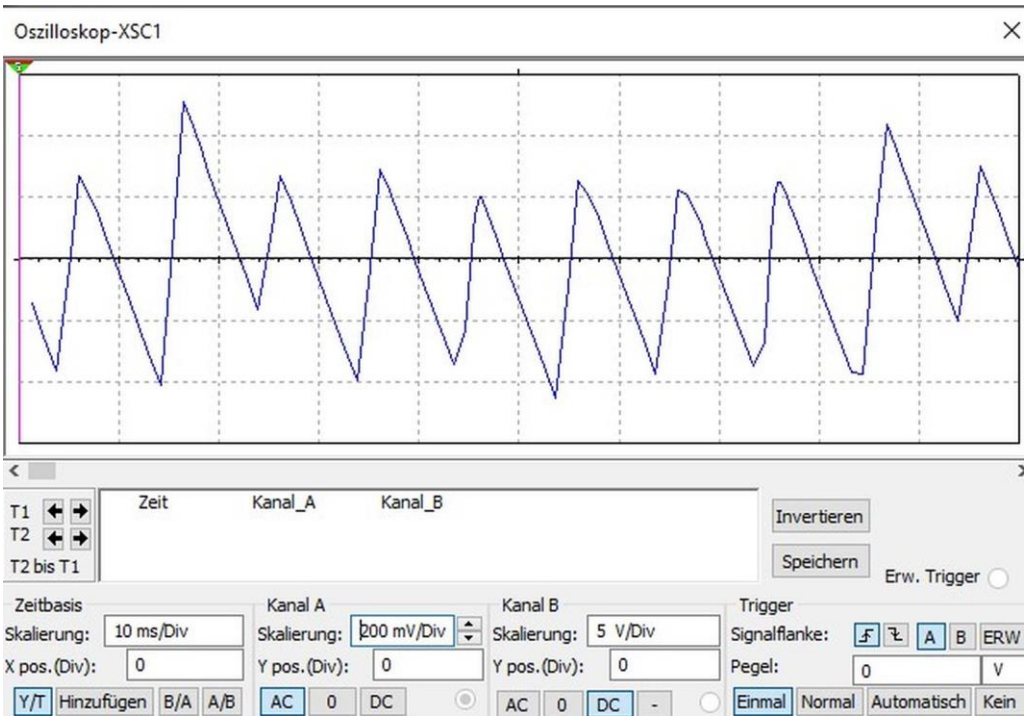


Figure 04-27 – Ripple voltage

GTT_010880

For components that are operated with a defined direct voltage and a tolerance, these tolerances must not be undercut or exceeded. The ripple voltage indicates whether these tolerances are exceeded or not.

Please try combinations of resistor loads and capacitor sizes (remembering that some capacitors are polarized). You should be able to see certain combinations result in almost completely removing the voltage ripple.

15.6 Review Notes

16 Transistors

16.1 Introduction

The transistor is a semiconductor device for controlling mostly low electrical voltages and currents. They are mostly used as on/off switches in integrated circuits in microelectronics.

Its function is that an electrical resistance can be controlled by an applied electrical voltage or current.

Figure 04-28 – Bipolar transistor

GTT_010881

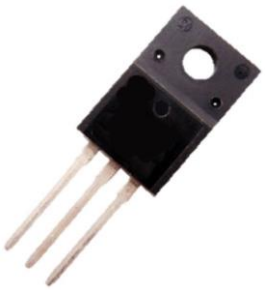


Figure 04-29 – Field effect transistor (FET)

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There are two important groups of transistors:

- Bipolar transistors
- Field effect transistors (FET)

They differ from each other by the type of actuation.

16.2 Bipolar Transistor

A bipolar transistor is a transistor in which negatively charged electrons and positively charged defect electrons contribute to current transport. It is controlled by an electric current and is used for switching and amplifying signals without mechanically moving parts. Bipolar power transistors are designed for switching and amplifying higher currents and voltages.

Bipolar junction transistors (BJTs) have the following key advantages:

- Low cost
- Ability to control a high load current across the collector emitter path with a low base-emitter current
- Wide range of current gain
- High switching speed

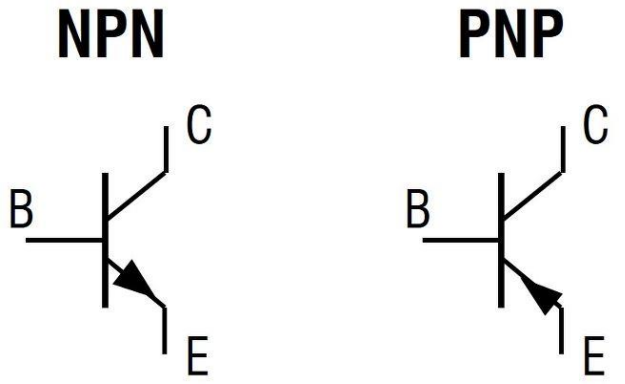

Figure 04-30 – Circuit symbol: Bipolar transistor

GTT_010883

Subdivision of bipolar transistors

- npn types
- pnp types

The letters indicate the doping of the respective layer.

Designation of the three connections

- Collector (C = collector)
- Base (B = base)
- Emitter (E = emitter)

Basically, a bipolar transistor always forms two p-n junctions connected against each other, similar to the one in a diode.

The direction of the arrow can also be explained with the technical current direction, which always runs from positive to negative. The arrow is always on the emitter side and points in the direction of the technical current direction. In the circuit symbol, the difference between pnp and npn is expressed by reversing the direction arrow between base and emitter.

In design, the bipolar transistor is a combination of three alternating p- and n-doped semiconductor layers (npn and pnp, respectively). The base is a particularly thin layer between collector and emitter. The emitter is more highly doped than the base, which in turn is more highly doped than the collector. This asymmetrical structure causes different behavior in normal and inverse operation.

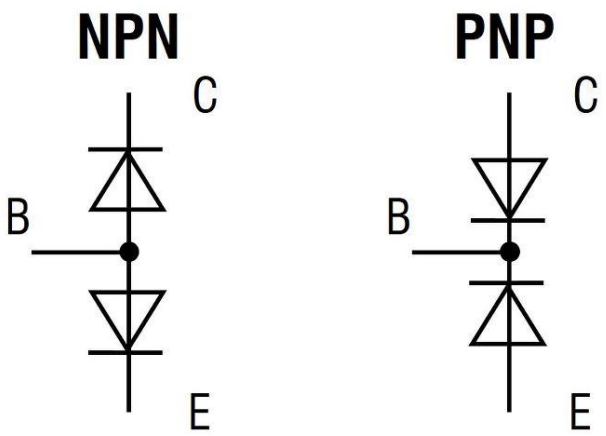

Figure 04-32 – Equivalent circuit diagrams: Bipolar transistor

GTT_010886

A bipolar transistor consists of two p-n junctions. Due to the fact that each p-n junction can be switched in the forward or reverse direction, there are four possible types of wiring. The most common type is the forward region. Here the emitter-base junction is connected in the forward direction and the base-collector junction in the reverse direction.

An electric current I_B between base and emitter controls a stronger current I_C between collector and emitter. The ratio of the two currents is in the range of approximately 4 to 1000 depending on the transistor type and is referred to as the amplification factor B.

Bipolar transistors operate both linearly and nonlinearly, depending on the range of base-emitter current. Outside the current range specified in the transistor's respective specification, the relationship between the base-emitter current and collector-emitter current (also called amplification) ceases to be linear. The bipolar transistor can therefore be operated in one of three operating modes:

- Active

  Most versatile and powerful operating mode and probably the most common application. The transistor can be used as an amplifier for the base current and proportionally amplify the current from the collector to the emitter.

- Saturation

  The transistor actually serves as a short circuit between the collector and emitter, and the current flow between the two is usually unrestricted.

- Blocking mode

  Here, the transistor represents an interrupted or open electric circuit, with no collector-emitter current flowing.

16.3 Field effect transistor (FET): Design and function

Compared to bipolar transistors, **no current flows across p-n junctions in field-effect transistors**. The electrical conductivity of a semiconductor channel can be changed by an external electric field and thus the switching or control function can be realized. Field-effect transistors are very well suited for use in integrated circuits.

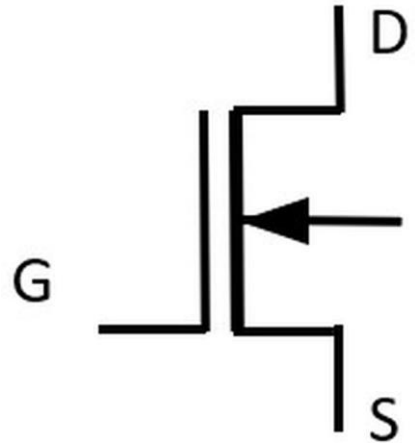

Figure 04-34 – Connections: Field effect transistor

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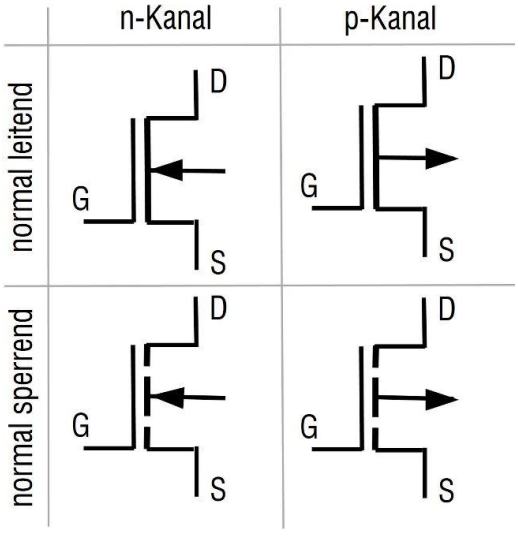
D	Drain	**S**	Source
G	Gate		

A field-effect transistor (FET) consists of differently doped layers of a base material, usually silicon.



Sperrend = blocking

Leitend = conductive

Figure 04-35 – Circuit symbol: Field effect transistor

GTT_010888

The connections on a FET are called

- Source = S (inflow)
- Drain = D (outflow)
- Gate = G (gate)

The operating current flows between S and D. Between S and D there is a channel whose conductivity is influenced by the voltage between S and G. The gate thus acts as a control electrode on the channel. The gate of a field-effect transistor is made of metal and its insulating layer is made of silicon oxide. **Since there is no electrical connection between the channel and the connections, the field-effect transistor operates without current and thus without power.**

Through various manufacturing processes, the channel can be designed as a

- Self-conducting channel

  It allows the current to flow without a control voltage. When a control voltage is applied, the charge carriers are forced out of them, so that its resistance increases.
- Self-blocking channel

  If no control voltage is applied between S and G, it has a very high resistance. When the control voltage is switched on, charge carriers accumulate in the channel, which thus becomes electrically conductive.

Depending on the channel type and the type of charge carriers in the channel, a distinction is made between different FETs. Due to the operating principle of a field-effect transistor with a self-blocking channel, it is initially non-conducting. No current flows in the make circuit between source and drain. A positive charge at the gate draws electrons from the silicon base material into the channel.

They are collected below the insulating layer and are available there as freely moving charge carriers for the current between S and D. When the gate capacitance is charged, only a brief current flows, but this makes the actuation practically power-free. During a test, the gate, once charged, remains effective even when the test probe is removed again.

16.4 MOSFET – Metal Oxide Field Effect Transistor

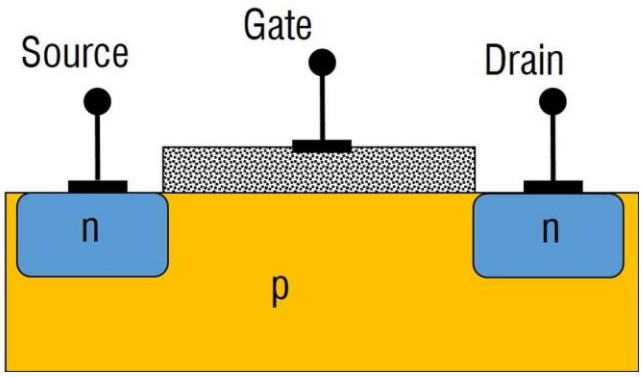


Figure 04-56 – MOSFET

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A MOSFET is an active component with at least three connections (electrodes):

- Source = S (inflow)
- Drain = D (outflow)
- Gate = G (gate)

There are designs where an additional connection B (bulk, substrate) is led to the outside. This is in turn connected to the chip rear side. A voltage at the chip rear side could generate additional electrical fields, which in turn affect the channel and cause a malfunction. However, the “Substrate” connection is usually connected internally to the “Source” connection.

A MOSFET is a particular type of transistor that belongs to the insulated gate field effect transistors. It acts like a voltage-controlled resistor. Via the Gate-Source voltage U_{GS}, the resistance between Drain and Source R_{DS} and thus the current I_{DS} (simplified ID) can be changed. The change in resistance in the MOS structure is due to the formation (enrichment types) or pinching off (depletion types) of a conducting channel under the gate.

16.5 States of a bipolar transistor switch stage

There are a total of four states that a transistor can assume as a switch. These states are also called operating points (AP).

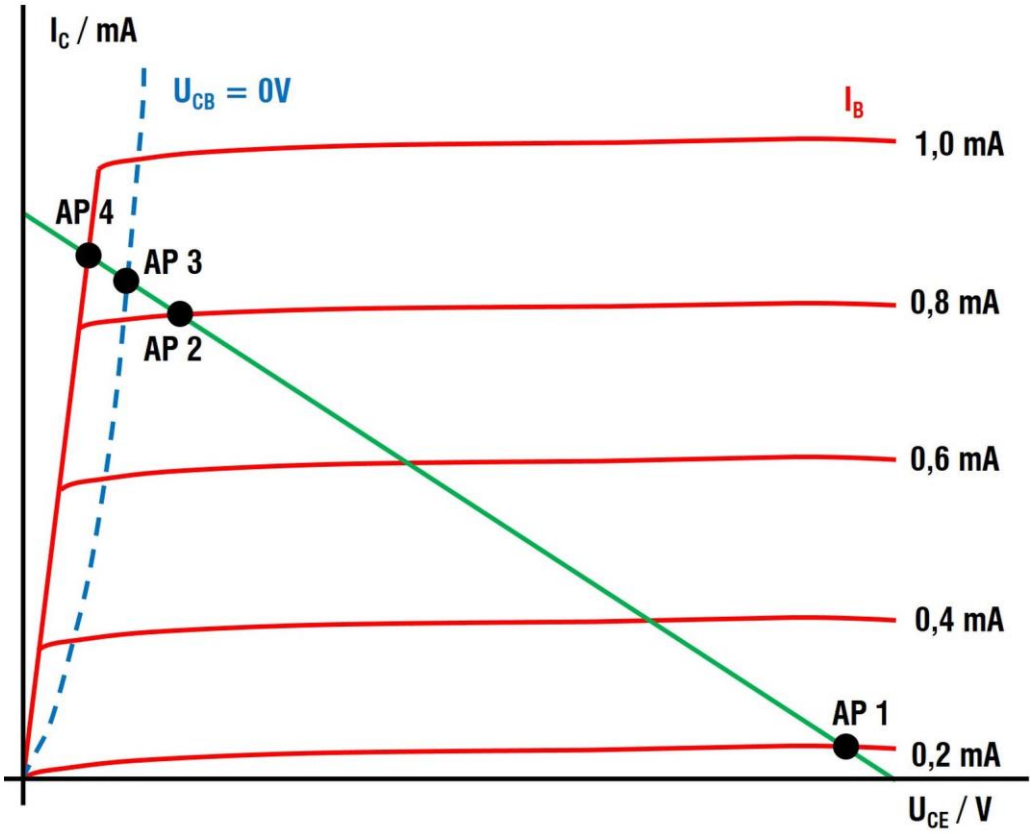

Figure 04-42 – Operating points of a transistor

GTT_010895

Operating point	Conductivity
AP1	Blocking state of the switch stage
AP2	The transition to the conductive state takes place between AP1 to AP2
AP3	Start of the overamplification range Up to AP4 the transistor can take on any operating point.
AP4	Saturation state Despite an increase in the base current, the collector-emitter voltage does not drop any further.

Green line = DC load line: The DC load line of a transistor shows the relationship between the current and voltage of the circuit under consideration for a given load.

Overamplification

If the transistor is operated as a switch, it is usually overamplified. In this state, it switches more quickly into the conducting state, which means that the switch-on time is shortened. At the same time, the switch-off time is extended, since the transistor crystal is flooded with charge carriers during this process. The blocking state is not reached until all charge carriers are removed and the blocking zone is then built up.

16.6 IGBT

The Insulated-Gate Bipolar Transistor (IGBT) is the most commonly used power semiconductor in industrial and automotive applications. It is a central component in:

- Converters for all types of electric drives
- Battery charging systems
- Solar systems
- Wind turbines

Figure 04-59 – IGBT

GTT_010912

Depending on the design, there are IGBTs with reverse voltages ranging from 300 V in discrete housings to high-power components in module form with up to 6500 V.

Currents of up to several 1000 A can flow in the process.

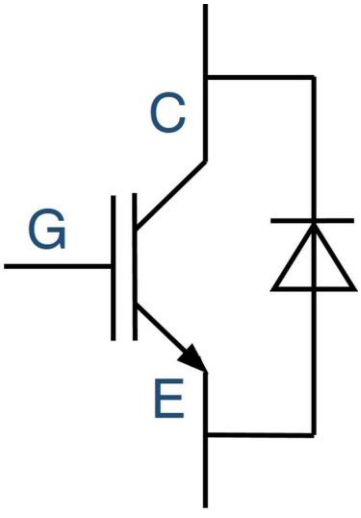

Figure 04-60 – Circuit symbol: IGBT

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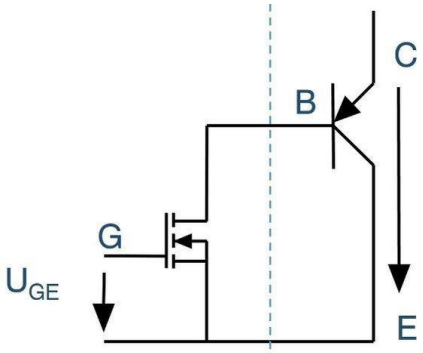

Figure 04-61 – Equivalent circuit diagram: IGBT

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Left	Insulated-Gate Transistor
Right	Bipolar transistor

The designation of “Insulated-Gate Bipolar Transistor” means that it is a bipolar transistor with an insulated gate. The gate is a MOSFET in its structure.

It therefore combines the advantages of:

- **the high current and high reverse voltage of bipolar transistors.**
- **the capacitive, almost powerless actuation of a MOSFET.**

The designations of the connections are:

- Collector (C)
- Gate (G)
- Emitter (E)

The equivalent circuit diagram shows only the mode of operation with the circuit of two separated components. The real-life version consists of an integration at the chip level.

For switching, a positive Gate-Emitter voltage U_{GE} must actuate the MOSFET.

The applied voltage at the collector allows the base current to flow through the bipolar transistor and the MOSFET. The bipolar transistor switches through and the operating current can flow. To switch off, the voltage at the MOSFET must be $U_{GE} \leq 0$ V. The base current comes to a standstill and the bipolar transistor blocks.

Due to the capacitive behavior of the MOSFET, the gate requires only a small current to charge the gate capacitance. Its average value is so low that the control power is practically zero.

The IGBT is optimized for fast switching of switching frequencies up to 30 kHz. In certain circuit topologies, the switching losses can be reduced and higher switching frequencies can be achieved. At the same time, it can conduct current in only one direction.

In contrast to the MOSFET, no freewheeling diode, the "body diode", is created during the manufacture of IGBTs. However, since such a freewheeling diode is necessary in almost all applications to protect the Collector-Emitter path from a current in the opposite direction caused by mutual inductance, an additional freewheeling diode must be installed.

When selecting them, care must be taken to ensure that a diode suitable in switching speed is added.

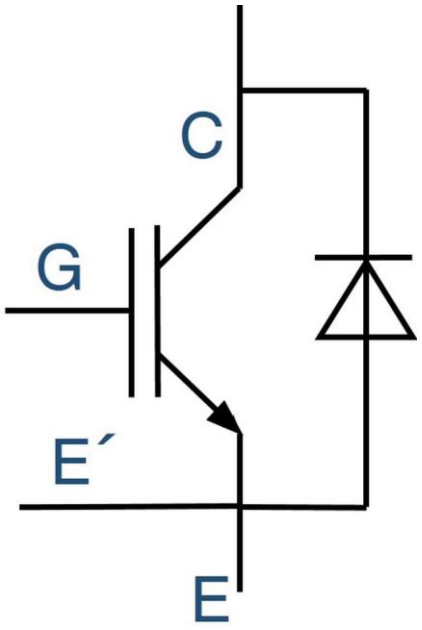

Figure 04-62 – Auxiliary emitter: IGBT

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IGBTs with integrated freewheeling diode can have an auxiliary connection on the emitter to improve the switching behavior, which reduces the leakage inductance contained in the gate circuit. No load current flows through this auxiliary emitter. This results in a clean switching operation which also reduces EMC.

In high-voltage vehicles, IGBTs are generally used to set up power inverters:

- They receive supply voltage from the traction battery

  They can then alter frequency, amplitude and the number of output phases

Since no current flows at IGBTs when they are switched off and no voltage drops across the component when they are switched on, they are regarded as ideal switches. They do not generate any power loss and therefore no heat. Their efficiencies reach around 99 %. Nevertheless, cooling of the components is necessary.

Many IGBT housings have an electrically active rear side, which is the collector. Thus, only IGBTs that have the same collector potential may be located on a common heat sink. Insulation to prevent short circuits reduces thermal transfer, which reduces the usability of the semiconductors.

16.7 Exercise 28: Bipolar transistor as switch

IMPORTANT: To avoid damaging transistors before the base of the transistor the current needs to be controlled, typically by a resistor before (R_{VOR}).

Objective:

Here you will experience the operation of a Bipolar transistor as it is actuated by the pulse generator and controls a relay signal circuit. At this time, we do not have a load connected to the relay. In addition, the free-wheeling diode shown next to the relay is integrated already in the UniTrain relay component, take a look at the picture on the plug-in component.

We should also be able to see with the capacitor across the current limiting resistor the effect of assisting the ON-OFF response of the transistor. We can also measure the current through the base to emitter as well as the current in collector and emitter and see two things, one the amplification factor of using a small current to allow a large current and also that the base current adds to the collector current for the total current at the emitter, thus showing some energy is used to control the bipolar, later we will compare to a FET transistor.

Now build a circuit in the UniTrain I training system on the instructions of the trainer, in which the transistor acts as a switch. Use Figure 04-38 as a template. As instructed by the trainer, measure the voltage U_{BE} and the voltage U_{CE} with the oscilloscope and document the result. Use the following equipment and components for this purpose:

- UniTrain I
- Function generator
  - U= 5 V
  - f = 10 Hz
- Supply voltage U_{BV1} = 15 V
- Capacitor C_1 = .47 uF
- Resistance R_1 = 3.9 kΩ
- Transistor Q_1 = BC 547
- Relay BP 2123 P7P
- Oscilloscope

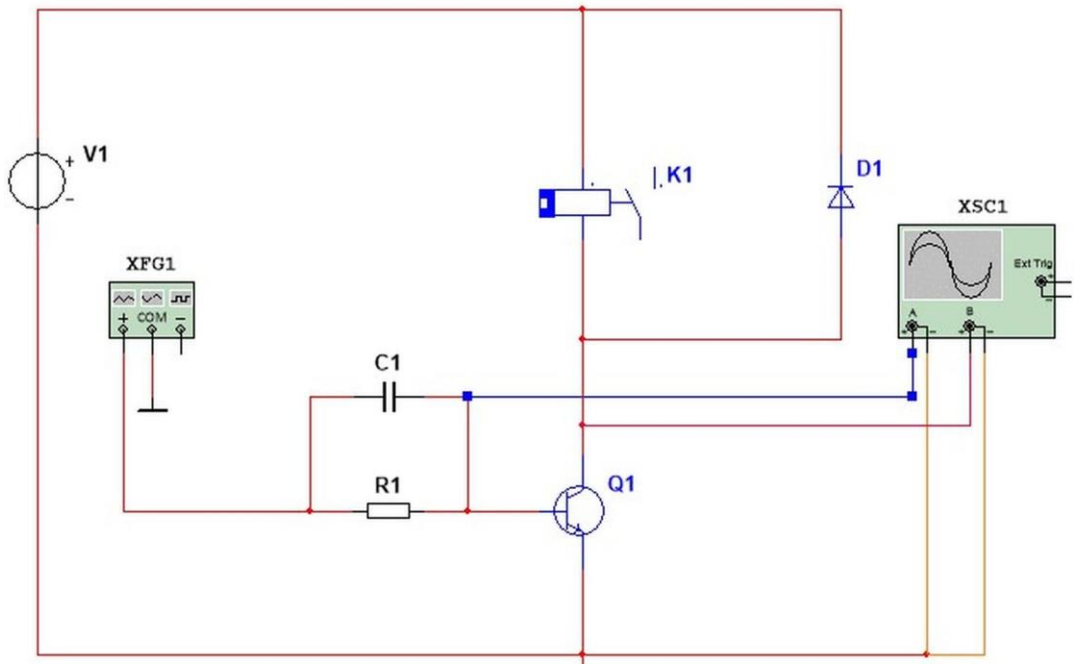

Figure 04-38 – Circuit diagram: Transistor as switch

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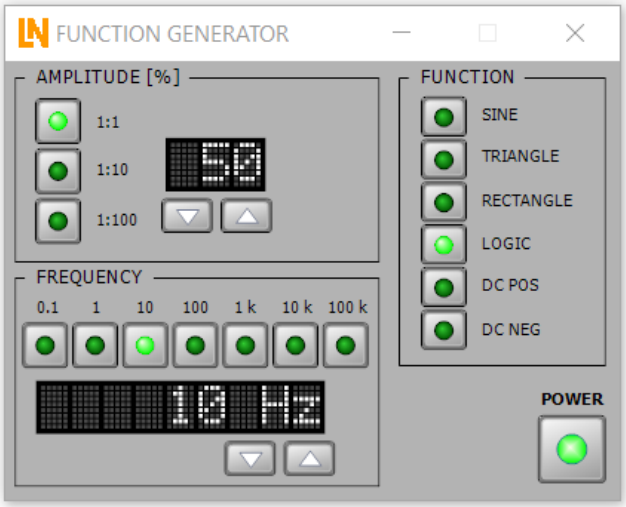

Settings of function generator

a) Using the oscilloscope, measure voltage U_{BE} and voltage U_{CE}
(red = channel B = U_{CE}; blue = channel A = U_{BE})

Then discuss the voltage-time functions with the trainer. In particular, clarify the function of capacitor C_1!

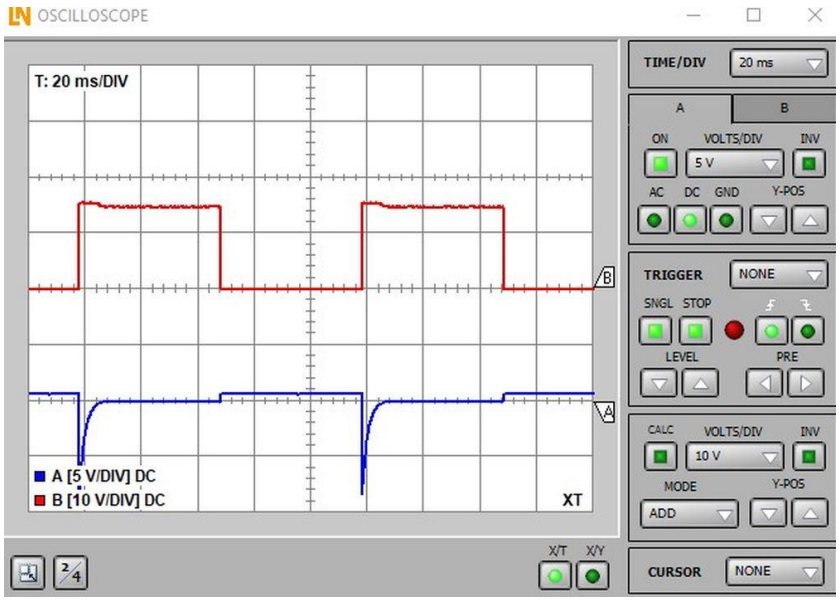

Figure 04-40 – U_{BE} and U_{CE}

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b) To clarify the function of C_1, apply a direct voltage of + 5 V to the base series resistor in the constructed circuit instead of the function generator, as instructed by the trainer. Then measure the base and collector current with the virtual ammeter. Use these values to calculate the DC current amplification.

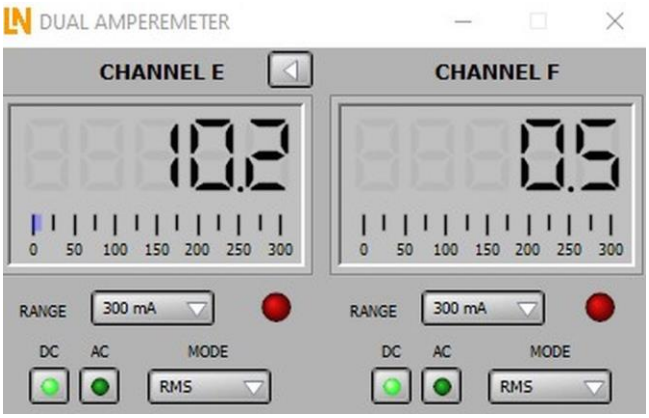

Figure 04-41 – DC amplification

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Channel E = Collector current

Channel F = Base current

The DC current amplification (B) can be calculated using the measured current at I_B & I_C

$B = I_C / I_B$

For your calculations:

17 Day 3 Review

Draw a **single-phase rectifier** bridge circuit.

Draw a **three-phase rectifier** bridge circuit.

Where are these rectifiers used?

What are transistors primarily used for?

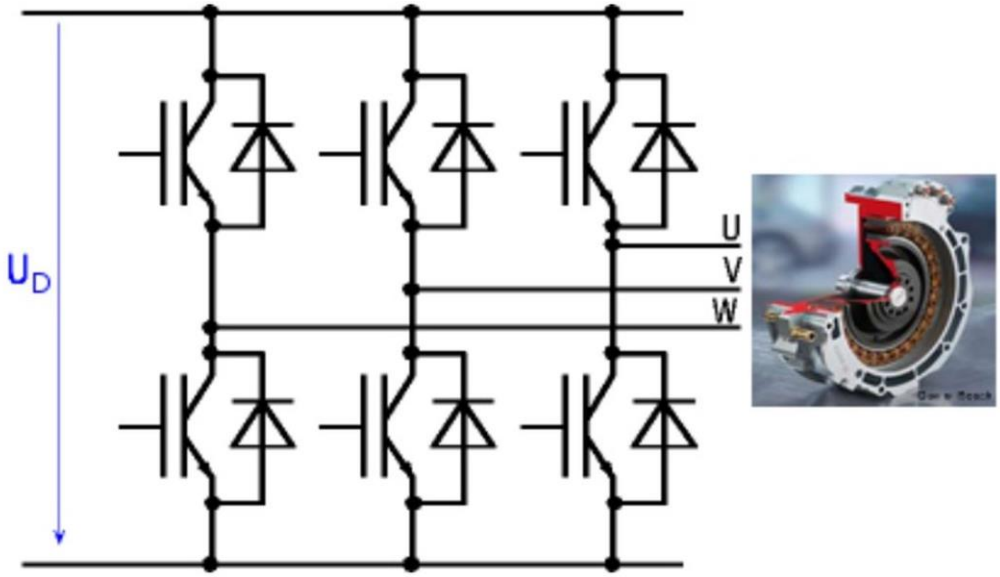
IGBTs combine the advantages of which types of transistors? What are the advantages?

What is the function of a diode? What about a Zener diode?

How do you test a diode?

18 Function of an inverter

An inverter is an electrical device for converting direct voltage (DC) to alternating voltage (AC). The component part usually referred to as inverter in automotive engineering is also referred to as power inverter, phase converter or converter. In addition to the motor alternator, the inverter is an essential component of the three-phase current drive.



Structure of an inverter

GTT_013728

The direct voltage is supplied to the inverter by the high-voltage battery or by the intermediate circuit connected to the high-voltage battery. The DC/AC converter provides the alternating voltage for the motor. In doing so, it controls the amplitude and the frequency of the output voltage.

The main components of the inverter form IGBTs (bipolar transistor with insulated gate electrode; insulated gate bipolar transistor). The transistors used as switching elements generate a sinusoidal alternating current from short pulses with high frequency through pulse width modulation (PWM). The transistors are actuated by microprocessors. In doing so, the transistors periodically reverse the direct voltage with high frequency. The output alternating current is thus made up of small pulses with different widths, which roughly correspond to a sinusoidal path. Almost arbitrary frequencies and voltage levels can be generated at the output.

The use of IGBTs in power electronics is based on their high voltage and current limits. IGBTs operate in the voltage range of up to 6.5 kV and can control currents of up to 3600 A. This results in a controllable performance of up to 100 MW. However, the switching frequency is limited by the switching losses and is a maximum of approx. 200 kHz.

General Design of a Power Electronics / invertor:

For any of our vehicles that have an electric machine to drive or assist the drivetrain, there will be a power electronics, sometimes called invertor.

The main task of the inverter is to convert DC voltage into the appropriate AC voltage with the correct frequency and strength.

Alongside the motor-generator, the Power electronics (DC/AC converter) is one of the main components of the AC drive system. At the DC/AC converter, the direct voltage of the high-voltage battery is distributed to the phase connections of the drive motor so as to produce a 3-phase voltage.

When the motor-generator is functioning as a generator, the 3-phase alternating voltage generated by the electric machine is converted into the direct current voltage that is required to charge the high-voltage battery.

The DC/AC converter is also needed to control the rotational speeds of the electric drive motors.

The DC/AC converter uses pulse width modulation to generate the alternating voltage for the motor.

Operating Principle of a Power Electronics / invertor:

The direct current voltage is fed into the DC/AC converter by the high-voltage battery or by the rectified 3-phase alternating voltage (of the intermediate circuit voltage UD) from the motor-generator.

The DC/AC converter provides the alternating voltage for the motor.

In doing so, it controls the amplitude and the frequency of the output voltage. The control principle used is pulse width modulation.

IGBTs (insulated-gate bipolar transistors) are the main components of the DC/AC converter. Freewheeling diodes protect against reverse current/voltage from the motor (voltage peaks).

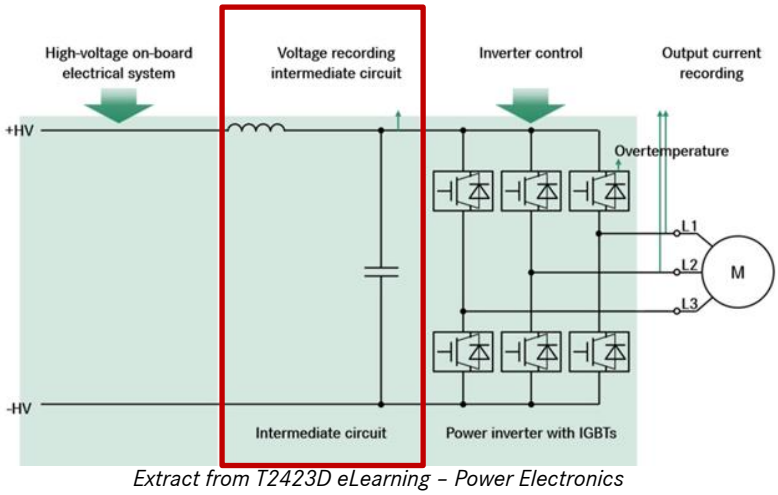
DC/AC converter circuits and converters operate at switching frequencies between 1 and 20 kHz. The higher the switching frequency, the less the ripple in the motor current. However, high switching frequencies result in greater switching losses. Thus, the output power drops while the motor heats up more at high switching frequencies due to the harmonics. This is caused by greater losses in the iron packet of the motor.

The high switching frequencies likewise have a negative effect on the EMC problem. Motor lines must be shielded. Attention must be paid to appropriate line lengths (capacitance of the line).

Motor filters may also be used.

18.1 Intermediate Circuit

We often hear the phrase intermediate circuit when discussing a power electronics or invertor.



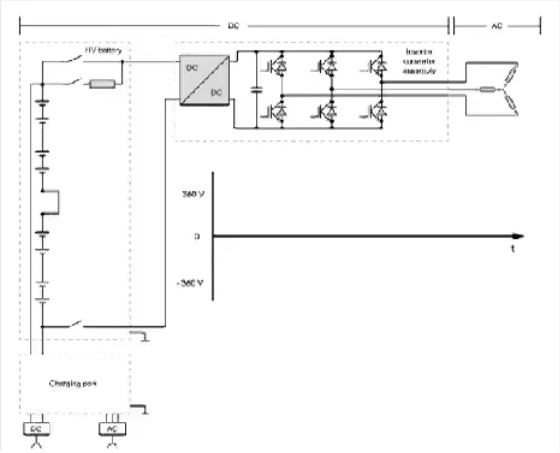
Extract from T2423D eLearning – Power Electronics

An intermediate circuit is an electrical device inside the DC/AC converter which acts as an energy storage unit and couples multiple electrical networks at an intermediate current or voltage level by means of converters.

In principle, the indirect, static DC/AC converter consists of a rectifier feeding a direct voltage intermediate circuit and a power inverter that is supplied from this intermediate circuit. The intermediate circuit consists of a capacitor to smooth the direct voltage and inductive loads to suppress interference. **Because of the size of this capacitor, it can be life threatening when working on or around if there is a defect in the system**. Both uncontrolled and controlled bridges are used as rectifiers.

LN software demonstrates the operation of an inverter showing the intermediate circuit and DC link.

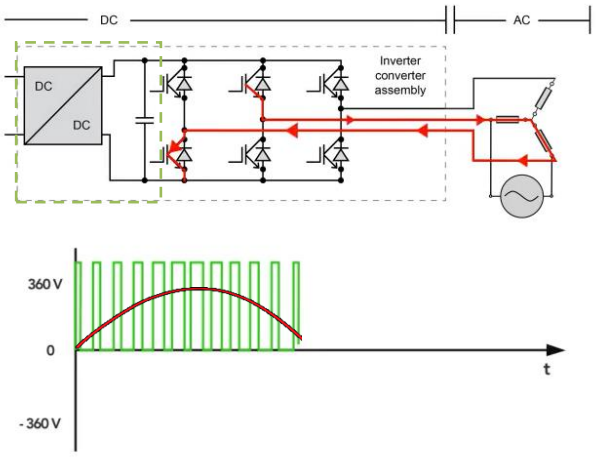
The animation shows the path of the conversion to a three-phase AC voltage going to the motor in a star configuration.



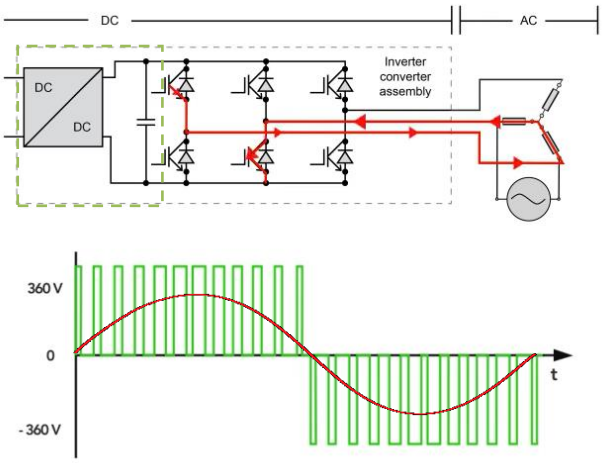
The DC link is the output of the DC/DC converter and is essentially the power supply for the IGBTs.

The controller will provide a PWM signal to the respectful transistors and with each period will increase or decrease the duty cycle. This will effectively provide us with an increasing and decreasing voltage, the top half of our AC sinusoidal wave. This will be directed to the coils of the motor for example U phase and will leave via the V phase.

Notice how the PWM duty cycle is changing each period from a small duty cycle to a long duty cycle and back to a short duty cycle



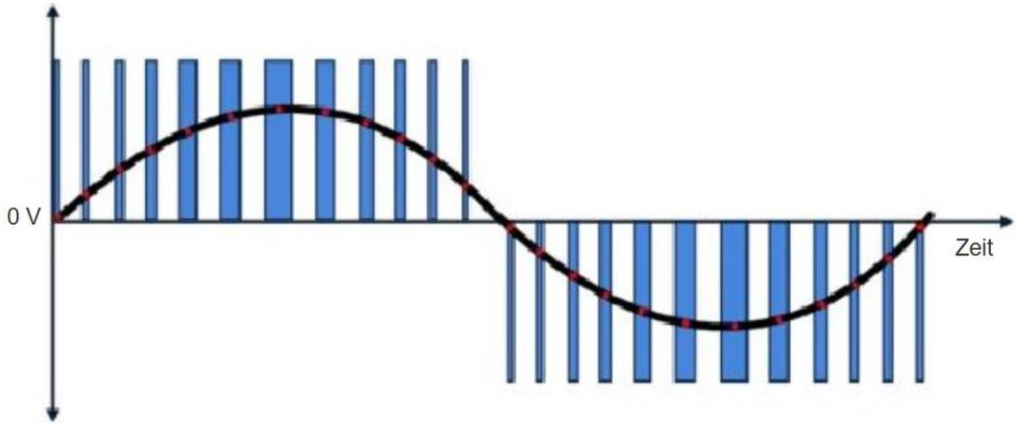
Notice in the second image we are now using two different IGBT's and through same PWM duty cycle principle have created a sinusoidal wave in the opposite direction, essentially our negative wave.



This type of sequence is repeated for all phases with some overlapping to create our three-phase supply to the electric motor. Of course, this is just a representation to get the concept across.

Changing the duty cycle will change the power and changing the frequency of these actuation blocks will increase or decrease the motor speed.

18.2 Pulse width modulated signal

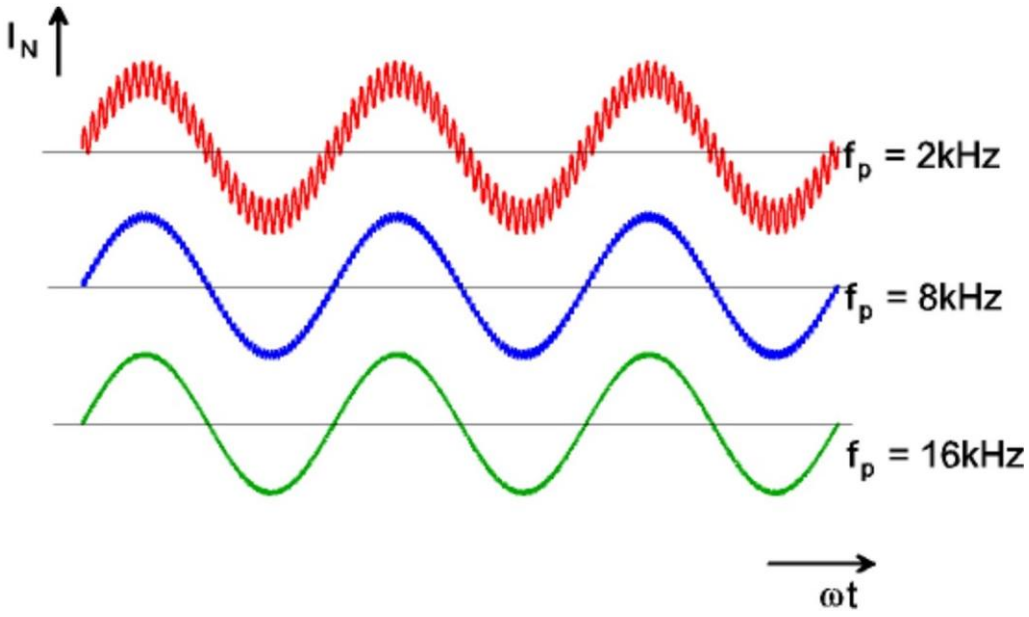


Principle of pulse width modulation

GTT_013729

DC/AC converter circuits and converters operate at switching frequencies between 1 and 20 kHz. The higher the switching frequency, the less ripple there is in the motor current. However, high switching frequencies result in greater switching losses. Thus the output power drops while the motor heats up more at high switching frequencies due to the harmonics. This is caused by greater losses in the iron packet of the motor.

The high switching frequencies also have a corresponding negative effect on EMC problems (electromagnetic compatibility = EMC). Motor cables must be shielded. Attention must be paid to appropriate cable lengths (capacitance of the cable). Motor filters may also be used.



19 Electric motor

19.1 Electromotive principle

The electromotive principle is a physical law describing the conversion of electrical energy into mechanical energy. It is based on the **Lorentz force.**

This arises when a current-carrying conductor is in a magnetic field. It acts on the moving charge carriers in a magnetic field. This physical relationship is called the electromotive principle. It is used in the electric motor to convert electrical energy into mechanical energy.

The Lorentz force acts both perpendicular to the electron flow and perpendicular to the field lines of the magnetic field. Its direction of force can be determined with the help of the three-finger rule.

If the current flows parallel to the field lines of the magnetic field, the magnetic field cannot exert any force on the electrical conductor. The Lorentz force is therefore = 0.

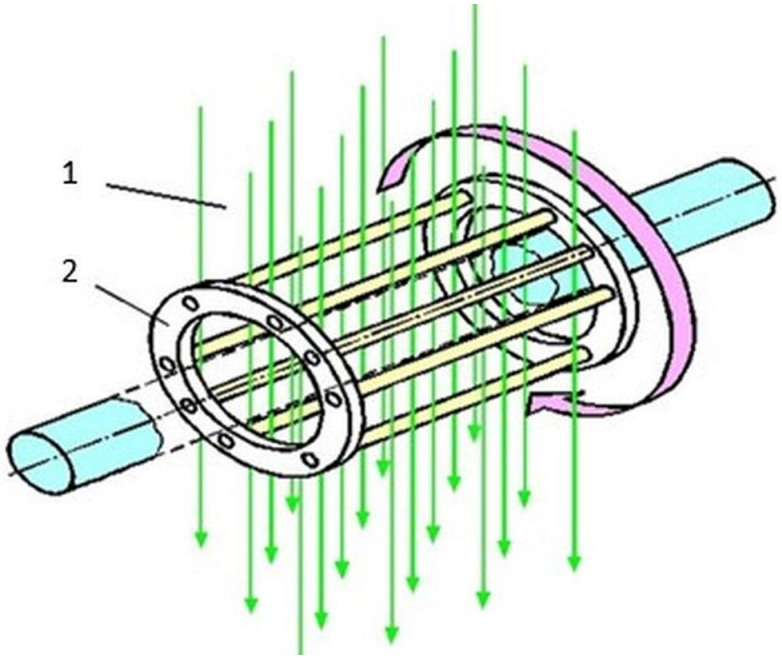


Figure 05-02 – Electric motor principle

GTT_010919

1	Rotating magnetic field
2	Squirrel cage

In engineering, this effect is used in electric machines. They basically have a stationary (stator) and a rotating (rotor) part. The rotor is mounted on a shaft and can rotate thanks to ball bearings.

In high-voltage drive technology, the stator is the fixed component of the electric machine.

A rotating magnetic field is generated in the stator or more precisely around it, which is largely guided in an iron circuit.

To produce power, this requires several current-carrying windings connected to a three-phase system and a package of stator plates.

Depending on the functional principle of the motor, the rotor consists of either permanent magnets or coil packages in a cage.

It is mounted in the stator housing on both sides.

19.2 Rotating Field and Current

A rotating field is a magnetic field that rotates continuously about an axis of rotation. Rotating fields are generated to drive three-phase AC motors and independently starting AC motors. The rotating field magnetically drags along the rotor mounted on the shaft of the motor.

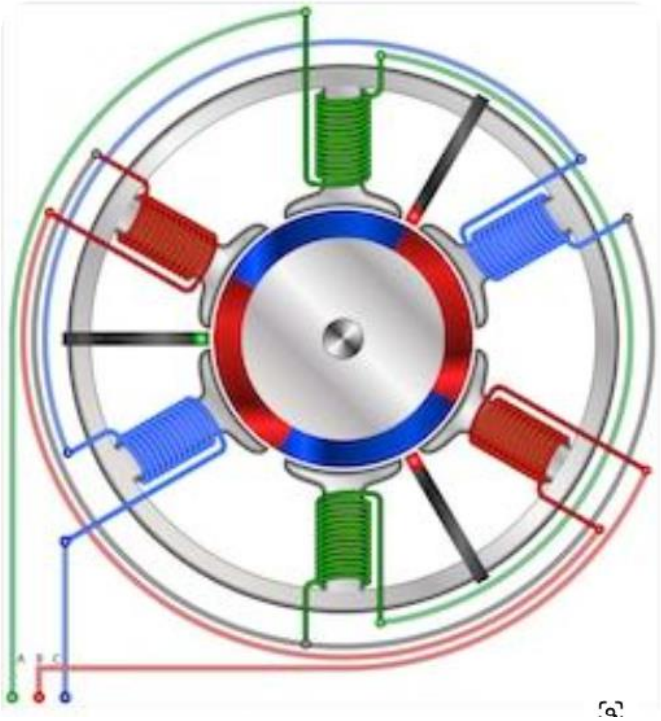


Figure 05-05 – Generation of rotating field

GTT_010921

Such a rotating field is generated by the circular arrangement of coils and actuation of these with time-staggered alternating currents and the associated magnetic fields. To use a three-phase alternating current, six coils are used for this purpose in the simplest case, with the respective opposite coils are connected to form a pole pair. They thus form the two poles of an electromagnet. The pole pairs are actuated alternately so that the rotor is continuously rotated by the rotating field moving on a circular path.

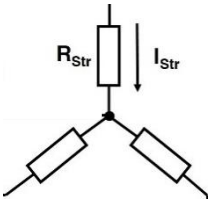
The speed of the motor can be changed by changing the frequency of the alternating current.

The maximum power output is controlled by the current sent to the coils.

A rotating field can also be generated by a two-phase alternating current. It is formed by the time offset of two alternating currents by 90°. Such electric machines have a lower efficiency due to the poorer utilization of the conductor cross-sections.

19.3 Linking The Strings

Stator windings can be connected in a delta or star connection. When connecting electric machines, it should be noted that different voltages must be applied to or are produced at the windings depending on the type of connection. In motor vehicles, this connection is usually specified by the manufacturer.



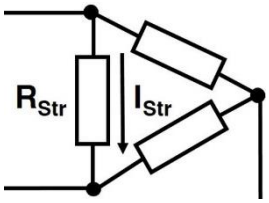
Star connection

In a star connection, the conductor voltage (phase voltage) is divided among the individual winding strings by a factor of $1/\sqrt{3}$. This leads to favorable insulation conditions. $\sqrt{3}$ is the interlinking factor. The voltages at the windings are larger and the winding currents smaller.

The Conductor voltages do not correspond to the string voltages:
$U_L = \sqrt{3}\ U_{Str}$

The conductor currents correspond to the string currents:
$I_L = I_{Str}$

The string ends of the windings are connected to a common center point, the "star point". Since three-phase machines have symmetrical loads, it is not necessary to connect the star point.



Delta connection

In the delta connection, the conductor currents (phase currents) are divided among the individual winding phases by a factor of $1/\sqrt{3}$. It therefore offers advantages for high currents and low voltages. A disadvantage compared to the star connection is the comparatively high insulation cost. A delta connection is used with powerful electric motors. In a delta connection, the voltages at the windings are smaller and the winding currents are larger.

The conductor voltages correspond to the string voltages:
$U_L = U_{Str}$

The conductor currents do not correspond to the string currents:
$I_L = \sqrt{3}\ I_{Str}$

The string end of one winding is connected to the beginning of the next winding. A center point, as in the star connection, does not exist.

Star-Delta connection

In industry and working machines (but not in automotive engineering), the star-delta connection (YΔ connection) is used for starting larger three-phase AC motors with squirrel-cage rotors (e.g. large circular saws) as of a power of 4 kW. The power consumption of the motor in the starting phase is 1/3 of the power in a star connection compared to a delta connection.

19.4 Synchronous Motor

In a synchronous motor, its permanent magnet rotor rotates at the same speed and thus synchronously with the rotating field. This permanent magnet rotor consists of a permanent magnet whose magnetic flux density can be influenced by different materials and manufacturing processes. In the motors used in motor vehicles, optimized designs of the permanent magnets are positioned in the rotor in such a way that optimal motor performance is achieved. This is achieved, for example, by a V-shaped arrangement of the magnets.

For the calculation of the speed, the following applies to all synchronous motors:

$$n = \frac{f_1}{p}$$

p = Number of pole pairs (rotor)

f_1 = Frequency of the voltage applied to the stator

The motor speed can therefore only be changed by the following measures:

- Changing the number of pole pairs p, e.g. for pole-changing motors
- Changing the frequency f_1 of the supply voltage

Special measures are also necessary for safe start-up of synchronous motors. Modern inverters can generate a frequency and amplitude-variable network and thus realize the speed control of synchronous motors.

Electric motors are designed for constant magnetization. This means that the magnetic flux within the stator must remain the same at all frequencies. In the case of variable-frequency networks, certain conditions must be met for this purpose.

If a three-phase system with constant voltage is applied to the stator windings, the stator currents will change due to the inductances. This change occurs whenever the frequency changes.

If the frequency decreases, the stator current and thus the magnetic flux increase.

To keep the magnetic flux constant with changing frequency, the voltage must be changed at the same time. One way to keep the stator currents constant is to “control the characteristic” by means of a V/f characteristic.

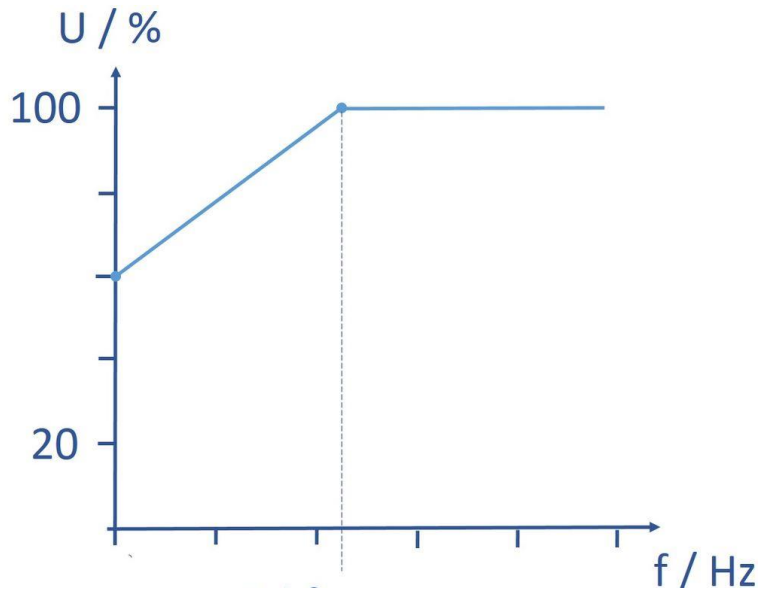


Figure 05-11 – V/f characteristic

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The voltage is increased from a starting point proportionally with the frequency up to a maximum value. This maximum value is the maximum voltage that can be supplied by the inverter. The frequency at which this maximum value is reached is called the cutoff frequency. The starting voltage is the minimum voltage at which the control characteristic starts. It compensates exactly for the voltage drop that occurs at the ohmic winding resistance at the nominal current.

Since the magnetization is proportional to the magnetizing current and thus in good approximation to the no-load current, the no-load current must remain approximately constant at all frequencies. The setting of a characteristic can therefore be checked by measuring the no-load current.

The advantage of the synchronous motor over the asynchronous motor is that it has a higher power density. This means that greater power can be achieved with a smaller design.

In terms of function, the following areas are considered:

- No-load
- Load

In no-load operation, the rotor consisting of permanent magnets rotates with the rotating magnetic field of the stator without deflection from its preferred position. In no-load operation, the north poles of the stator and the south poles of the rotor are always opposite each other and vice versa.

When loaded and thus decelerated, the rotor will lag slightly behind the targeted position, but will maintain its synchronous speed with the rotating field. The rotor will lag behind the rotating field of the stator by the pole wheel angle $\vartheta < 0$. This results in a mechanical drive torque on the shaft. This depends sinusoidally on the pole wheel angle.

M = Torque

$M = F_t \times r = - M_K \times \sin \vartheta$

At $\vartheta = - 90°$, the torque reaches its maximum value $M_{(- 90°)} = M_K$

This maximum value is referred to as the breakdown torque. If this value is exceeded, the synchronous machine can no longer develop any drive torque and therefore coasts to a halt.

For safety reasons, only about half the breakdown torque is used during operation:

$M \leq MN \approx ½ MK.$

If the electric motor is used as a generator, all relationships apply in the same way. In this case, the rotor precedes the rotating field of the stator by the pole wheel angle ϑ.

19.5 Asynchronous Motor

The operation of the three-phase asynchronous motor is based on the rotating field, which is radially directed in the air gap between the stator and the rotor.

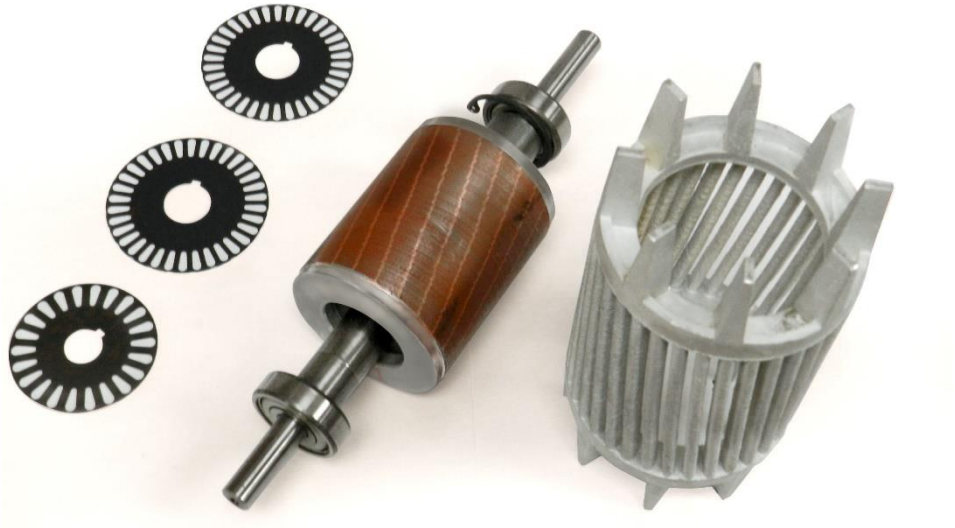
In operation, the rotor precedes the rotating field of the stator as a generator and follows it as an electric motor. The three-phase asynchronous motor has a passive rotor which is either permanently short-circuited (squirrel-cage rotor, short-circuited rotor) or occasionally short-circuited (slip-ring rotor).

Asynchronous motors that can be operated in single phase include:

- the capacitor motor
- the shaded-pole motor
- the starter motor

The rotor of a squirrel-cage rotor essentially consists of three components or materials:

- Pressed armature of dynamo laminations which are mutually insulated and have pre-fabricated cavities to accommodate the rotor rods
- Aluminum rotor rods and the shorting rings
- Shaft



Courtesy: Bodine Electric Company

In the asynchronous motor, the speed *n* must be functionally lower than the speed n_0 of the rotating field so that a torque can be generated.

With an unloaded machine, the idle speed is close to the speed of the rotating field.

Under load, the speed drops and is approximately 5% to 15% below the speed of the rotating field at nominal load.

This speed difference is called slip and is defined as a deviation from the synchronous rpm. It has the formula symbol **s**.

$s = (n_0-n) / n_0$

When the machine is idling and unloaded, the slip is almost 0. It increases with increasing load and takes the value 1 when the motor is at a standstill. The resulting torque is proportional to the slip.

If the rotor moves synchronously to the rotary field, the magnetic flux through the mesh of the cage is constant, and no voltage is induced. The torque is or becomes 0.

If the rotor rotates slower than the rotating field, the magnetic flux changes. This induces a voltage in the rotor, which in turn generates a current. With low slip, the current is proportional to the rate of change of the magnetic flux. The field generated by the current in the cage is still small compared to the rotating field in the stator. Furthermore, it is 90° out of phase with the latter.

If the cage field increases, the cage current no longer increases proportionally to the slip and the phase shift decreases until the torque has reached its maximum. In operation, the usable torque lies between this maximum and the no-load condition.

During start-up with the rotor stationary, the cage corresponds to the secondary winding of a transformer. Counter-inductances in the lines and ohmic losses limit the power consumption.

Thus, the motor has a poor efficiency in the starting range and heats up strongly.

19.6 Summary: Synchronous and Asynchronous motor

Synchronous Permanent Magnet Motor

Advantages	Disadvantages
Higher efficiency	Use of rare earth minerals. The magnets of the permanently excited motor are made from the rare earth elements neodymium and dysprosium.
No slip. The speed of the rotor is directly dependent on the frequency of the three-phase alternating current.	It is not self-start and require extra windings for starting the motor.
Rigid coupling of the speed and the angular position to the operating frequency	The rotor requires an extra current supply.
Less overheating. Unlike the induction motor, during regenerative braking no high voltage is induced by the revolving field in the rotor. No high current flows which could overheat the rotor.	The initial cost is greater than Induction motor.
More compact design	
It operates best at lower speed	

Asynchronous (Induction) Motor

Advantages	Disadvantages
Permanent magnets are not required for its operation and can for that reason keep down manufacturing costs.	Lower efficiency (compared to synchronous at lower speeds)
Self-excitation and self-start capabilities	Slip. The rotor turns behind the rotating magnetic fields, at no load about 5% slip. When loads applied the rotor tends to slow and slip increases.
High speed capability, consistently high efficiency in operation with inverter.	
Easier start-up against high counter-torques on three-phase mains.	
More cost-efficient production due to reduced rotor design.	

20 Work, Power, Efficiency

Electrical Work

Electrical energy (E) is the energy that can be transmitted by electricity or stored in electric fields. Energy that is converted from electrical energy into other forms of energy (heat, mechanical energy) is called electrical work (W).

The unit of measurement for electrical energy and work is the watt-second (Ws) or, equivalently, the joule (J).

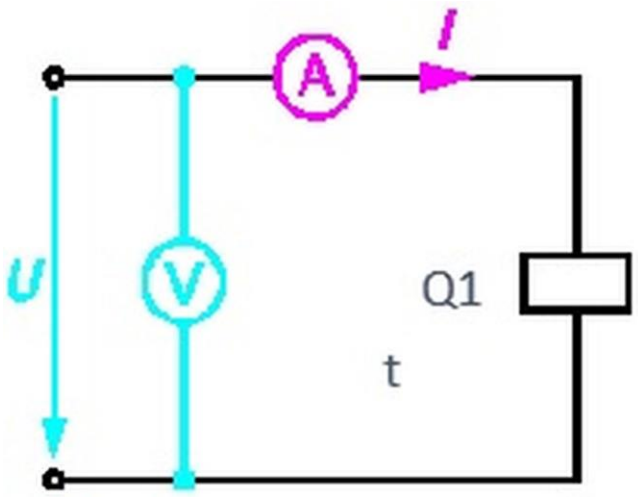


Figure 01-65 – Determination of electrical energy where t = time

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To determine the amount of electrical energy, current and voltage are measured over time. The measuring device takes the form of a meter, which measures current and voltage simultaneously.

This results in the following definition:

The electrical work performed by a generator is proportional to the voltage **U** and the amperage **I** of the current supplied, as well as to the time period **t** over which the current flow takes place.

$$W_{el} = U \times I \times t$$

The electrical work (W_{el}) corresponds to the amount of electrical energy that is converted into heat, for example, at this power and in this time.

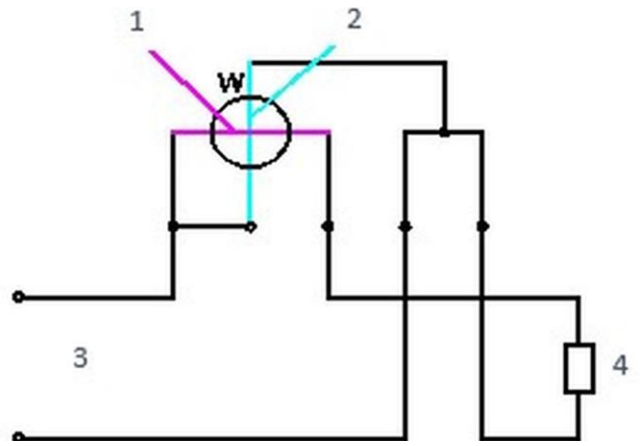


Figure 01-66 – Electrical energy measurement

GTT_010787

1	Current path	**3**	Feed
2	Voltage field	**4**	Current consumer

The counting equipment of the measuring system uses digital technology.

a) The electrical work is used to calculate energy costs, for example:

An electric vehicle is charged via a 230 V socket and over the duration of 12 hours with 10 A.

$V_E = V_P \times W$

V_E = Consumer end price

V_P = Energy price in dollars/kWh (for our example $0.33 /kWh)

W = Electrical work

Now calculate the cost of charging the electric vehicle using the formulas above:

Electric power

The electrical power P_{el} produced by a generator or required by a consumer is equal to the electrical work W_{el} performed over time t:

$$P_{\mathrm{el}} = \frac{\Delta W_{\mathrm{el}}}{\Delta t} = \frac{U \cdot I \cdot \Delta t}{\Delta t} = U \cdot I$$

This gives the following definition for electrical power: The electrical power P_{el} converted by an electronic component or electric circuit is proportional to the voltage U applied to the component and the current I flowing through the component.

$P_{el} = U \times I$

The power data are noted on each consumer.

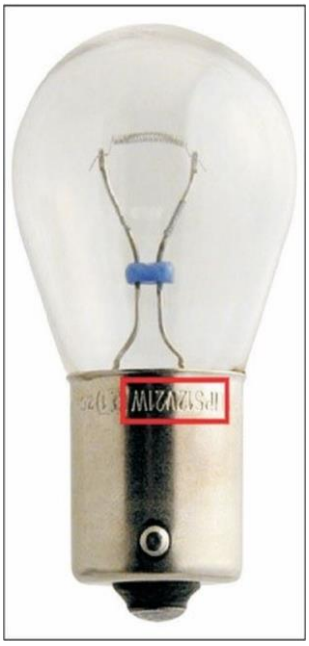


Figure 01-67 – Bulb power data
GTT_010728

The bulb shown in the example has an electrical output of 21 W at 12 volts.

The higher the power, the warmer the lamp and the brighter it shines. Other electrical consumers, such as electric motors for pumps, drives, TV units or vacuum cleaners, also have a type plate with information about the power they consume. The power consumption can be calculated from this information.

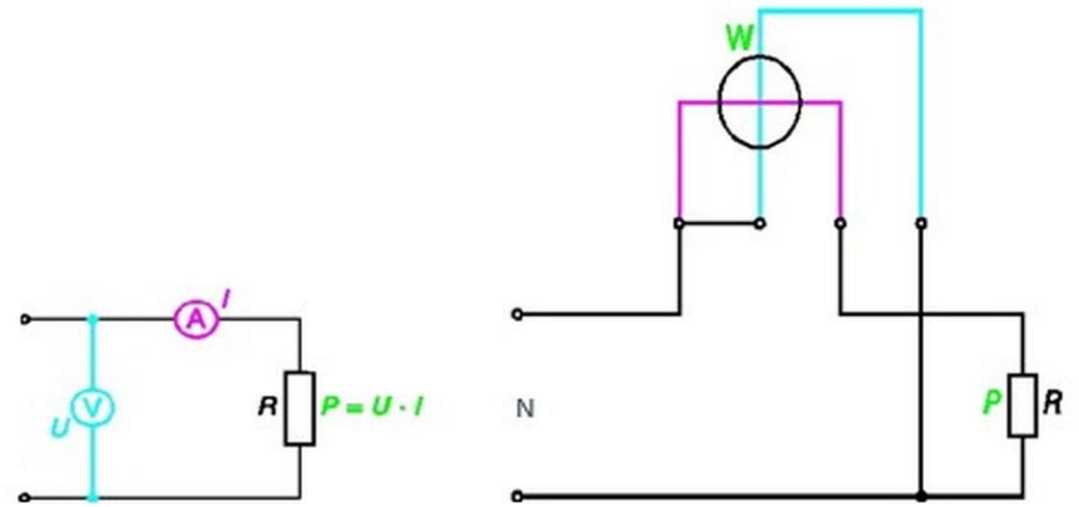


Figure 01-68 – Power measurement of circuit where N = Mains

GTT_010788

The following measurement values are required to determine the power:

- The current that flows through the consumer.
- The voltage applied to this consumer.

The following formula is used to calculate the power:

$$P = U \times I$$

The following units represent the physical values:

[P]: Power in W

[U]: Voltage in V

[I]: Current in A

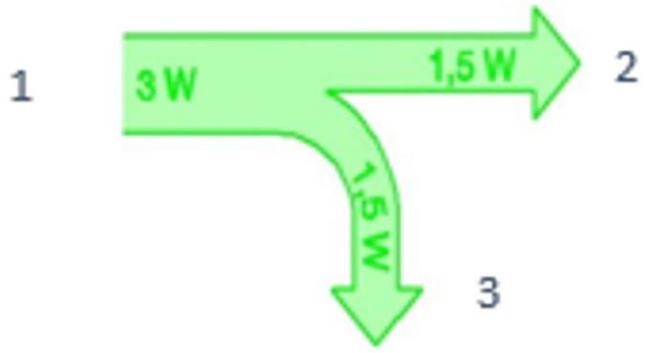
Electrical power can be represented by other physical quantities as follows:

Electrical power: 1 W = 1 V × 1 A
Thermal power: 1 W = 1 J/s
Mechanical power: 1 W = 1 Nm/s

EXAMPLE OF 21 W BULB:

c) **Determining efficiency**

The efficiency describes the degree of efficiency of a technical device or system. This usually represents the ratio of the useful energy E_{out} to the supplied energy E_{in}. Provided that there is no falsification by stored energy, the power can also be calculated as the ratio of the useful power P_{out} to the supplied power P_{in}. Usually, the efficiency is designated by the Greek letter η and as a ratio or percentage without unit of measure.



$$\eta = \frac{P_{out}}{P_{in}}$$

Figure 01-69 – Efficiency

GTT_010789

1	Power supplied (P_{IN})	**3**	Loss in heat
2	Useful power (P_{OUT})		

For example, P_{out} represents the mechanical power delivered to the shaft by an electric motor and P_{in} represents the electrical power delivered to the motor.

The difference between the power supplied and the power output is referred to as power loss. Every system has losses, which become apparent in the form of heat dissipation to the environment.

Figure 01-70 – Overall efficiency

GTT_010790

To determine the overall efficiency, the efficiencies of the components are multiplied together.

$\eta_{Total} = \eta_1 \times \eta_2 \times \eta_3 \ldots \times \eta_n$

20.1 Calculation of the Electric Power

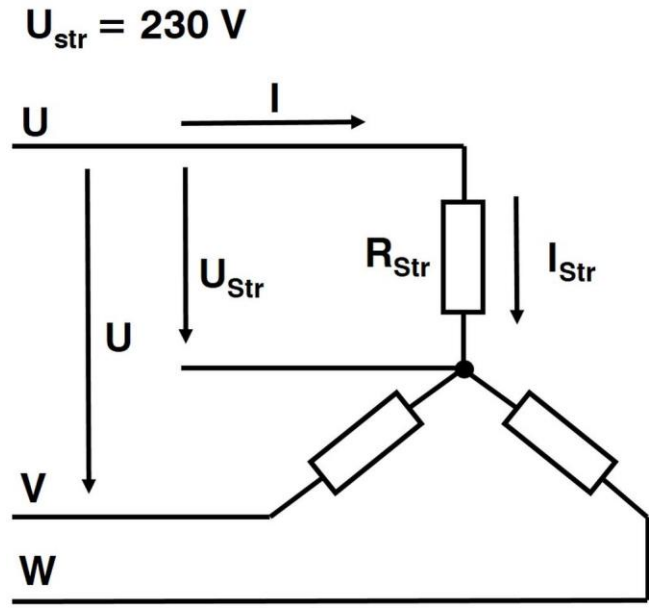


Figure 05-18 – Star connection

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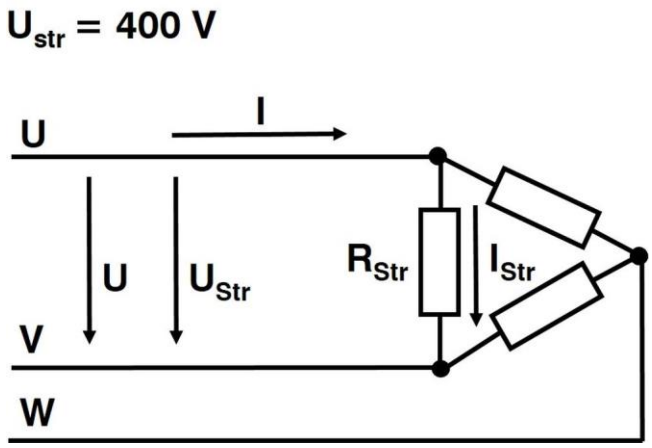

Figure 05-19 – Delta connection

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	Conductor current	Conductor voltage	String current
Star connection	$I = I_{Str}$	$U = \sqrt{3} \times U_{Str}$	$I_{Str} = U_{Str}/R_{Str}$
Delta connection	$I = \sqrt{3} \times I_{Str}$	$U = U_{Str}$	$I_{Str} = U_{Str}/R_{Str}$

Legend

I	Conductor current		R_{Str}	String resistance
U	Conductor voltage		$\sqrt{3}$	Linking factor
I_{Str}	String current		P	Active power
U_{Str}	String voltage		cosϕ	Power factor with inductive load

20.2 Electric Power with Direct and Alternating Current

Electric power is a physical quantity which indicates how much electrical energy is converted in a certain time. The formula symbol *P* is derived from the word *power*. It is measured in the basic unit of the watt (W).

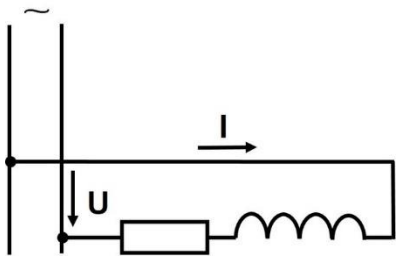

Figure 05-16 – Alternating current with inductive load component

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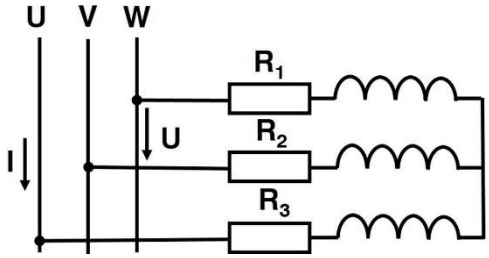

Figure 05-17 – Three-phase current with inductive load component

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U	Voltage (phase voltage)
I	Amperage

Electric power is measured differently depending on the type of current.

The following formulas are used for the calculation of apparent electric power with

direct current and alternating current. Note: RMS values should be used.

$$P = U \times I \quad \text{or} \quad P = I^2 \times R \quad \text{or} \quad P = U^2/R$$

When calculating the power of a three-phase alternating current (three-phase current), its conditions must be taken into account. Here the transmission is equally loaded under symmetrical load.

Formula for power calculation of a **3-phase and continuous power supply**:

$$\boldsymbol{P = \sqrt{3} \times U_L \times I_L}$$

L = Phase or Conductor (total)

20.3 Alternating and Three-Phase Current with Inductive Load

In the case of inductive load components, the effectively usable electrical power is referred to as the active power. It is the power share that is actually available for conversion into e.g. mechanical, thermal, etc. power. Another power component is the reactive power, which cannot be used for conversion. For the calculation of the active power, the respective power factor is added to the formula:

Active power with alternating current	Active power with three-phase current
$P = U \times I \times \cos\varphi$	$P = \sqrt{3} \times U_L \times I_L \times \cos\varphi$

We will get more into Active power and power factors shortly but let's step back to calculating electric power where we don't have an inductive load component for a little practice.

The following example allows you to do a calculation with the group which begins with limited information, but enough to calculate electric power on a 3-phase power supply.

Calculation of the electric power of a heating circuit

Now calculate the power of an electric heating circuit in which the three glow coils are connected in a delta connection. The following apply:

- 3-phase supply voltage = 400 V
- R_{Str} = 22 Ω

Formulas we will use are ohm's law and the power rule $P = \sqrt{3} \times U \times I$

Apparent power (S):

Apparent power is measured in volt-amperes (VA).

It is the total electrical power present in a power grid, regardless of whether it is actually used to perform tasks. Calculated from the product of the RMS values of voltage and current. Apparent power is made up of active power and reactive power. But it does not need to equal the sum of reactive & active power. Basically, what is supplied.

Reactive power (Q):

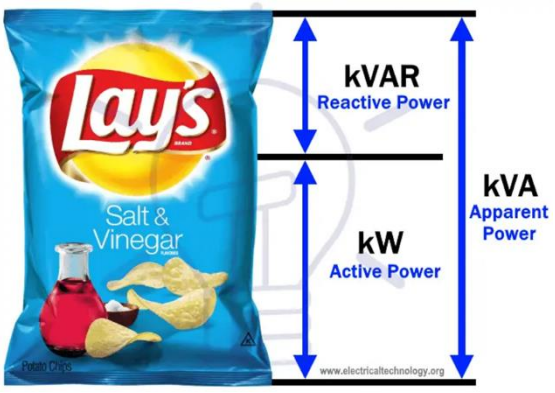
Reactive power is also measured in volt-ampere-reactive (VAR).

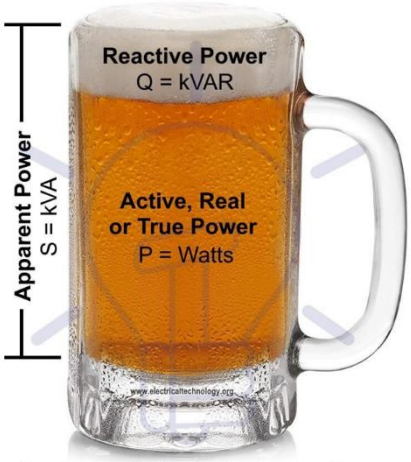
It represents the electrical power that flows back and forth between the phase conductors and the neutral conductor of a three-phase network, but does not perform any mechanical work. It is primarily generated by inductive and capacitive loads and is required for the operation of these loads, but does not contribute to the performance of tasks. At an ohmic load, the reactive power is zero. Basically, what is lost or not used in performing work.

Active power (P):

Active power is measured in watts (W).

It represents the actual electrical power used by a device or system in a power grid to do work. In other words, it is the useful power that drives a motor, generates light or operates electrical appliances, for example.





Beer Analogy of Active, Reactive & Apparent Power

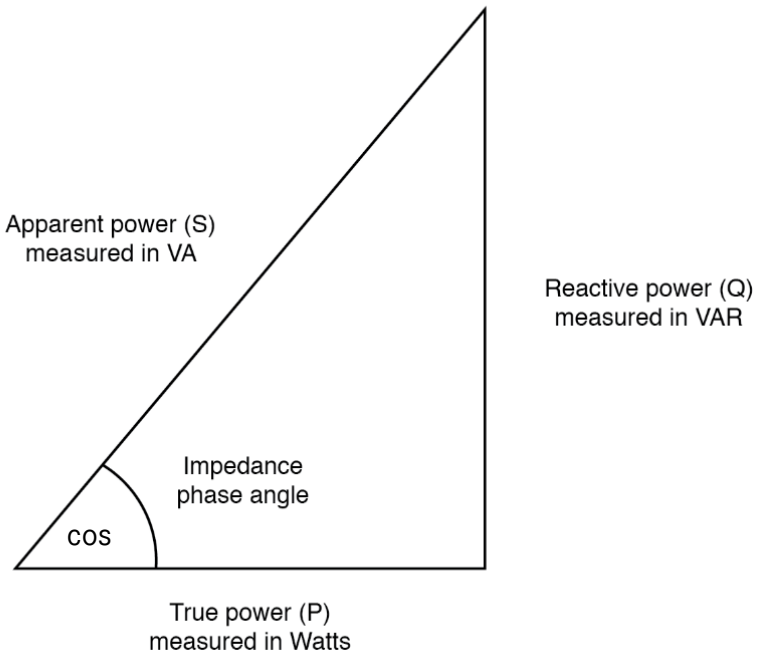
These three types of power—active, reactive, and apparent—relate to one another in trigonometric form.

We call this the power triangle and now you can relate to the connection to Pythagorean Theorem.

Pythagorean theorem can be used to solve the third side of a triangle once we know the other two sides, here we have replaced the traditional a, b & c letters with the three powers:

a	Active Power (P)	$P^2 = S^2 - Q^2$	or $P = \sqrt{S^2 - Q^2}$
b	Reactive power (Q)	$Q^2 = S^2 - P^2$	or $Q = \sqrt{S^2 - P^2}$
c	Apparent power (S)	$S^2 = P^2 + Q^2$	or $S = \sqrt{P^2 + Q^2}$

The "Power Triangle"



Power Factor is a really important piece of data used to describe the relation between apparent power and active power, as this can be used in formulas to determine for any given apparent power, what the active power will be.

Therefore, power factor indicates the efficiency of the system and is typically between 0 and 1.

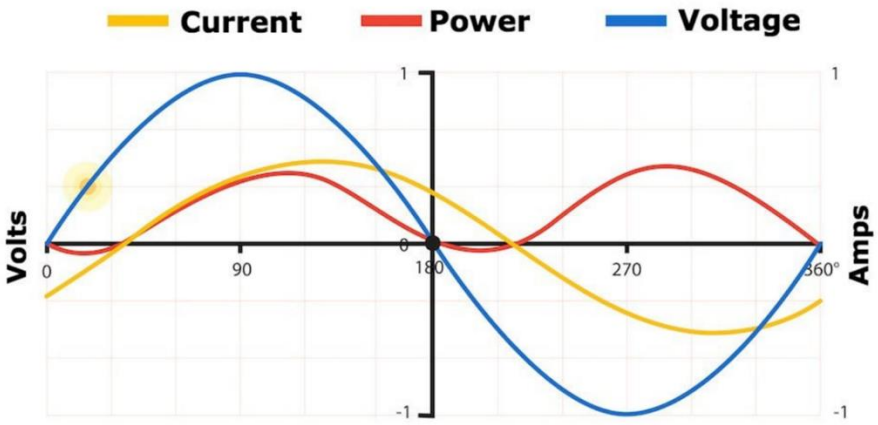
Ideal is 1 as indicates no losses, closer to zero is too many losses (reactive power).

The formula is: **PF = P/S** P = Active Power S = Apparent power

Quick example: Active power is 150 W Apparent power is 195.25

PF = 150/195.25 = 0.76824 (76%)

The power factor calculation is essentially the impedance phase angle if you take the inverse cosine of PF e.g. 0.76824 = 39.8°



We can find the inverse cosine of 0.866025 (cosφ) and see this equals 30°.

You can recognize in the current measurement sine wave that it is delayed which is the impact of the inductive. When the current and voltage are both on the same side of the x axis, we have our power being produced. With an AC voltage we produce power on both sides of the x axis hence the reason the power sine wave remains in the upper half most of the time. There are two areas on the diagram where the red line dips below the x axis, this is essentially the reactive power, and you will also note that this is the area the voltage and current are on opposite sides of the x axis and not on the same side. You will also notice that the delay of the current sine wave is 30° which matches our cosine angle & also the approx. degrees the power sine wave falls below the x axis.

20.4 Power Calculation of a Three-Phase AC motor

Objective:

In this exercise you will be able to perform power calculations for various conditions using given formulas and parameters. ($P = \sqrt{3} \times U \times I \times \cos\varphi$)

A three-phase AC motor is used to drive a high-voltage vehicle. Calculate the **apparent power** of this type of motor. The following apply:

- Battery voltage = 400 V
- Maximum power consumption = 215 A

Next, using the provided cosφ value, calculate **active power** of the motor.

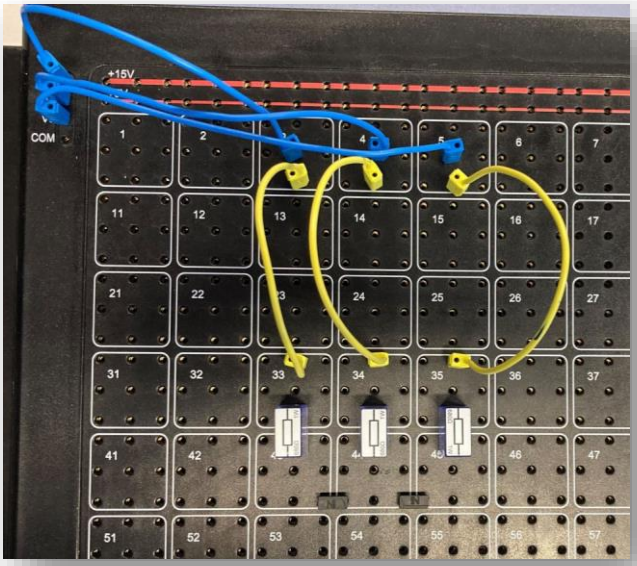
- $\cos\varphi$ = 18.19°

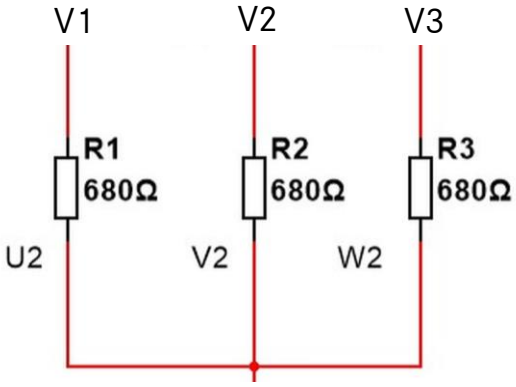
Now that you have active and apparent power, use them to calculate the power factor % of this motor.

Exercise 30: Output of a STAR circuit

Set up a star circuit of three resistors as shown in the figure below. Connect the three-phase current supply to the three resistors. Use the following components for this purpose:

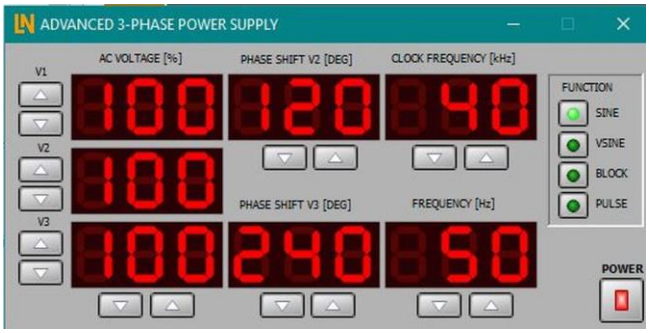
- Lucas-Nülle training system
- Multimeter 13 S
- Resistors R_1, R_2, R_3 = 680 Ω
- Three-phase current supply (V1, V2, V3)





A) Calculate the resistance between the external conductors V_1 and V_2 in the de-energized state. Before measuring the resistance, you must disconnect the connection to the power supply (blue cable).

In “Instruments > Power supply units”, select the extended three-phase current supply. Set the power supply at the three phases to 100%. Set a phase offset of 120° between V2 and V1 and 240° between V3 and V1 and select a frequency of 50 Hz.



Three-phase current supply settings

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B) Now measure the string voltage by voltage dropping one of the consumers. Then calculate for phase voltage and verify by measuring across two of the phases.

C) Make sure the current supply is POWERED OFF. Now calculate the phase current using the values you have just measured and calculated. Then wire your multimeter in series with the circuit to measure phase current. ASK INSTRUCTOR BEFORE POWERING ON. Then measure current and note below.

D) Now using the oscilloscope, measure the voltage of the two phases V_1 and V_2 relative to the star point (string voltage). Determine the effective value (RMS) of the string voltages from the signal. You can also observe the 120° offset.

E) Calculate the total electrical output of the star circuit.

f) **Simulation of a technical defect**

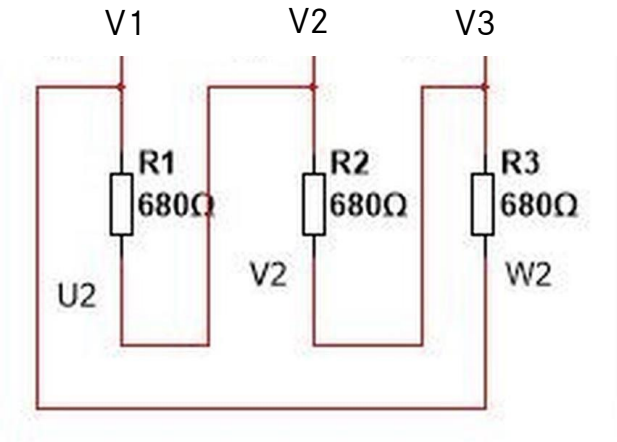
One of the phases breaks off and is no longer connected to the star circuit. Calculate the remaining output.

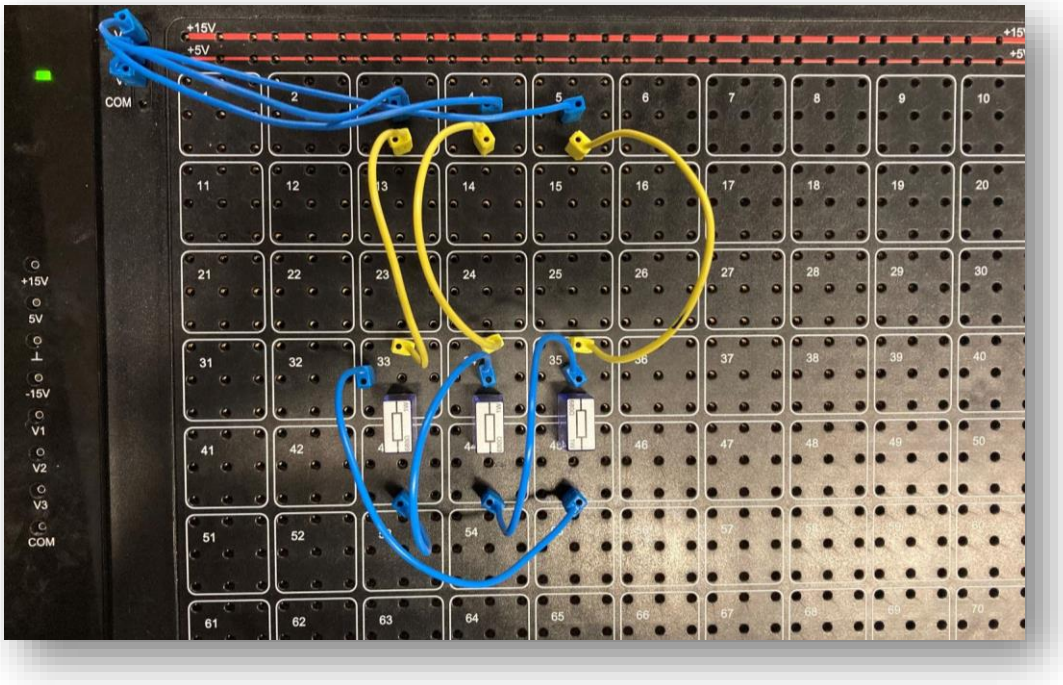
Draw a star circuit diagram in this condition to better visualize how current would flow through the circuit.

20.6 Exercise 31: Output of a DELTA circuit

Set up a delta circuit of three resistors as shown in the figure below. Connect the three-phase current supply to the three resistors. Use the following components for this purpose:

- Lucas-Nülle training system
- Multimeter 13 S
- Resistors R_1, R_2, R_3 = 680 Ω
- Three-phase current supply (V1, V2, V3)





A) Calculate the resistance between the external conductors V_1 and V_2 in the de-energized state. Check your calculated result by measuring the values. Before measuring the resistance, you must disconnect the connection to the power supply (blue cable).

B) Now measure the phase voltage with the multimeter across two phases and check whether it is equal to the string voltage by voltage dropping one of the consumers.

C) Calculate the string currents and the phase current. Again put your meter in series with the circuit and ASK INSTRUCTOR BEFORE TURNING ON. Now activate the three-phase current supply and check your calculation using measuring technology.

Compare the phase current of the delta circuit with that of the star circuit from the previous activity.

D) Now using the oscilloscope, measure the voltage of the two phases V_1 and V_2 across the strings. Determine the effective value (RMS) of the string voltages from the signal. You can also observe the 120° offset.

E) Calculate the electrical output of the previous star circuit and the current delta circuit. Compare the power consumption of the two and note your observations.

F) **Simulation of a technical defect.**

One of the phases breaks off and is no longer connected to the delta circuit. Calculate the remaining output.

Draw a delta circuit diagram in this condition to better visualize how current would flow through the circuit.

21 Using Drive Modules

21.1 Setting up the Drive Modules

The Trainer will gather you into groups and provide an overview of the additional UniTrain I equipment for the drive module.

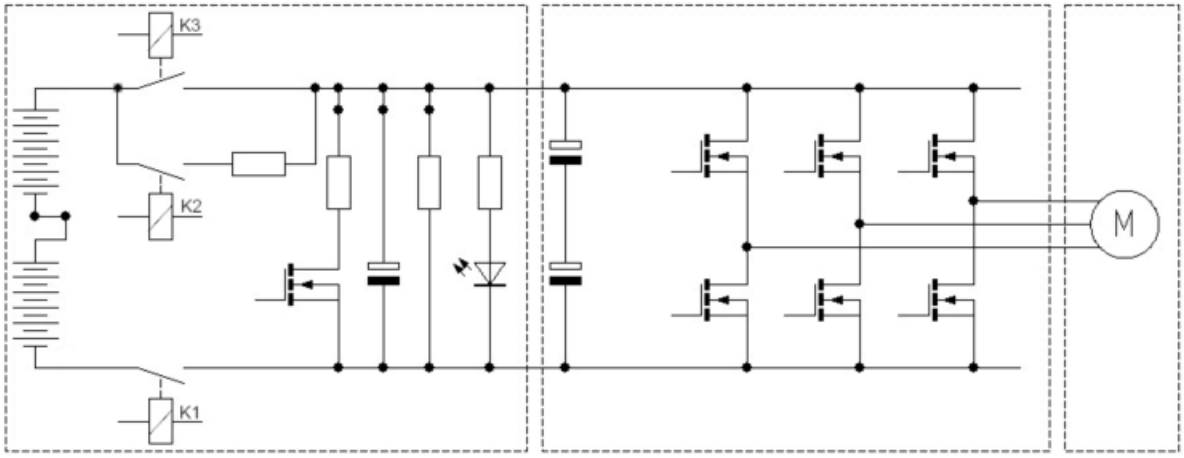
This includes:

- 3 x docking stations
- Battery module
- Power electronics / inverter / intermediate / DC link module
- Electric machine module
- Synchronous & Asynchronous rotor (coil winding rotor usually is not used)
- Various connector cables and bridge pieces
- Software menu changes (required additional software installation)

Trainer will lead you through:

- How to connect the components
- Identifying components on each module such as transistors, capacitors, DC link.....
- How to start the battery with the brake and ready buttons on the battery module
- Where to find the menus to control the electric motor and put the system into operation
- How to connect a 2 channel scope to measure a single phase to motor as well as the PWM control signal via the built in shunt resistor (optional may be to extend to show 4 channels with all 3 phases and one PWM control
- How to switch between star and delta motor configurations
- How to reverse direction of motor by changing the order of two of the three phases
- Where to find a help guide if the above is forgotten
- Demo of using a strobe light to see the synchronous motor operation and compare to asynchronous
- How to remove modules
- Experience how much easier an Asynchronous motor starts compared to synchronous

Later you will perform all of the above in separate exercises as well as explore further star & delta configurations including voltage and current measurements for conductor and strings to better understand these.

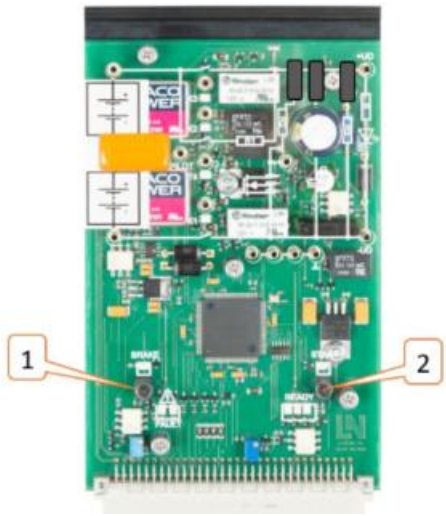


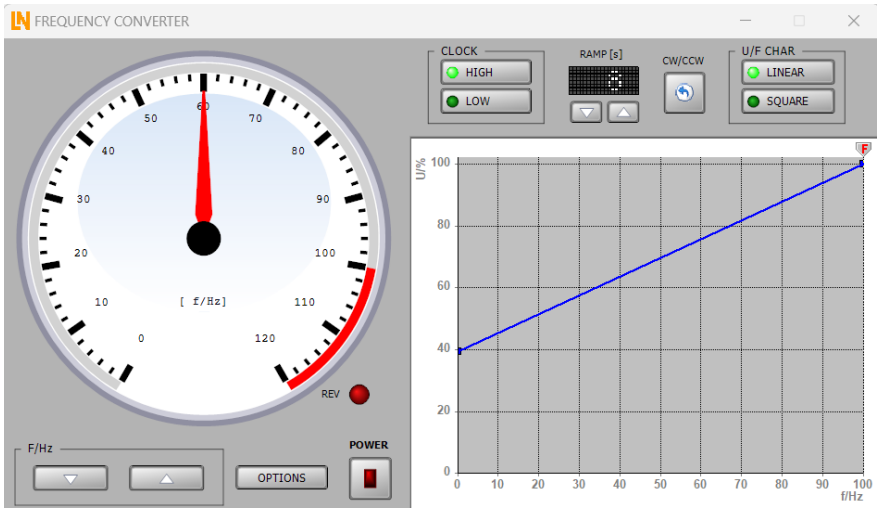
Objective:

In this exercise you will be able to setup the Drive Modules and be able to control the electric motor via the LN software.

You will now set-up the drive modules yourself, if you need assistance contact the Trainer.

You will set up a circuit according to image below and as per DEMO in the training system.





Once setup, you can see if the setup works by controlling the motor with the software.

Then try the following, see if the synchronous motor if operated at a low Hz, say 1-3, is smooth to start operating or is very ‘jerky’ in operation and may not even turn smoothly.

For comparison with the same settings, see how the Asynchronous rotor responds.

You can document your findings here if necessary:

21.2 Exercise 32: Current Measurement on Electric Motors

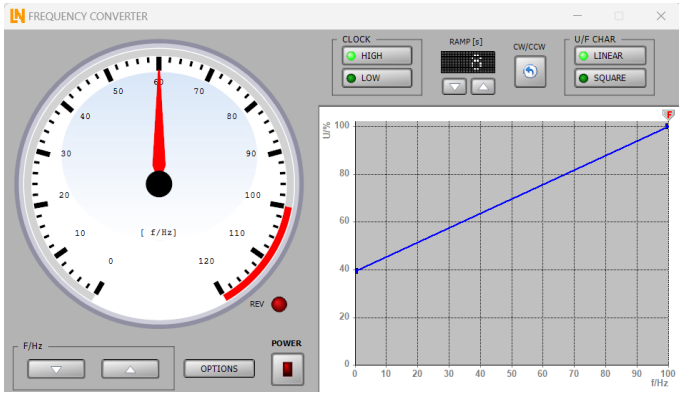
Objective:

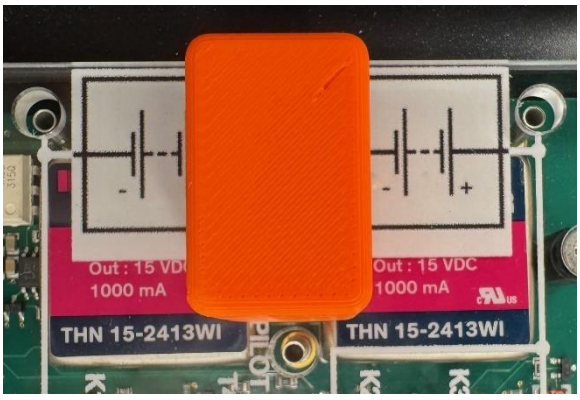
In this exercise you will be able to measure a phase string current in both star and delta configurations to further your understanding of each configuration. In addition you will measure phase (conductor) voltage as well as string voltage. You will be able to confirm through measurements the relationship between string and conductor voltage & also current and be able to recall which connection type has the same string voltage as conductor voltage and also which connection type has the same string current as conductor current.

You will set up a circuit in the training system according to Figure 05-06 or 05-07. Note the position of the white bridge connectors at the motor assembly.

Use the following equipment for this purpose:

- UniTrain I
- LabSoft
- Virtual ammeter





Make sure to set the frequency converter to the specifications in the picture. **Some of the battery modules on the boards have a 1000mA (1A) breaker** as shown in the picture on the right. Depending on your motor configuration this could lead to a high current draw on startup which could cause a fault on the board. Start at a lower frequency and slowly raise it to 60HZ. Best not to go over 70hz as well.

Take the following measurements at 60HZ:

Star:

Measure the current of one string at string bridge in **star** configuration.

Measure the phase current at U, V or W in a **star** configuration.

Measure the *voltage* between two phases (U-V) in ***star*** configuration

Measure the *voltage* between two phases (V-W) in ***star*** configuration.

Measure the *voltage* between two phases (U-W) in ***star*** configuration.

Measure the *voltage* of one string (U_1 – U_2) in ***star*** configuration.

Delta:

Measure the current of one string at string bridge in **delta** configuration.

Measure the phase current at U, V or W in a **delta** configuration.

Measure the *voltage* between two phases (U-V) in **delta** configuration.

Measure the *voltage* between two phases (V-W) in **delta** configuration.

Measure the *voltage* between two phases (U-W) in **delta** configuration.

Measure the *voltage* of one string (U_1 – U_2) in **delta** configuration.

IMPORTANT!

Use the virtual voltmeter for measurements, and set the voltage range to 50V
For current measurements make sure meter is set to AC amperage

21.3 Rotational speed/rpm control

RPM Control

The speed of a shaft is controlled to a desired value by an rpm control system. Depending on the situation at hand, this is done either at the torque-generating point (motor) or by selectively generating a decelerating torque (braking).

If a motor is operated at a constant speed independently of the load, this must be controlled by a controller unit. The actual value of the rotational speed is measured or calculated from the current. If there is a deviation from the specified value, the controller unit is adjusted according to the rotational speed of the motor. In drive technology, this type of control system is referred to as vector control.

Examples:

- Steam engine

  A throttle valve is actuated proportionally to the rotational speed by an rpm governor.
- Three-phase machines

  Frequency converters detect the actual rotational speed via the current and adjust accordingly.

Three-Phase asynchronous systems

The rotational speed is adjusted by the following factors:

- Number of pole pairs

  Imprecise, design-related influence. With a higher number of pole pairs, the rotational speed becomes lower.
- Frequency

  More precise and finer control. The stator frequency is proportional to the rotational speed of the rotating field.

  Due to the change in the stator rotating field, more magnetic field lines are cut. The resulting greater induction on the rotor accelerates it.
- Slip

  Slip control can reduce the speed. By reducing the stator voltage, the slip increases and the rotational speed decreases.

A speed change in three-phase synchronous motors is only achieved by the number of pole pairs and the frequency.

21.4 Exercise 33: Electric Motor Control Using PWM

Objective:

A learner builds the control system of a synchronous motor in the UniTrain I training system on the instruction of the trainer. Its speed is controlled with the help of the function generator.

Use the following devices for this purpose:

- UniTrain I training system
- Function generator U = 10 V
- Dual-channel oscilloscope

In the next step, connect the oscilloscope to one phase of the motor and adjust the signal. Now explain the signal, if necessary with the support of the trainer. Finally, the rotor is exchanged for a squirrel-cage rotor. Discuss the reaction together with the trainer and document it.

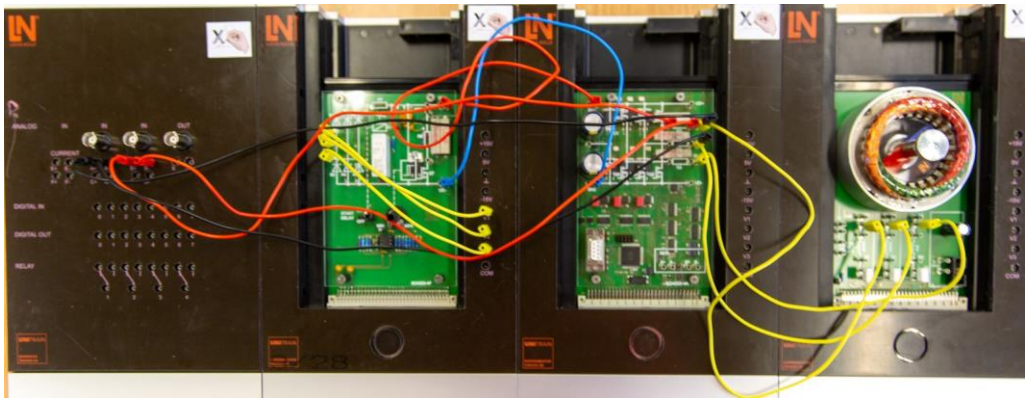


Figure 05-39 – Rpm control

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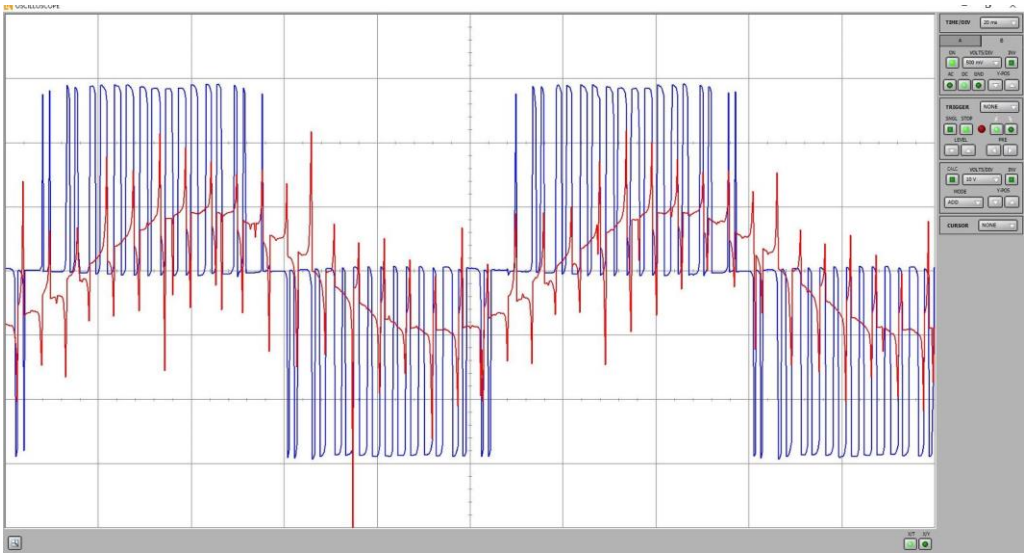

Figure 05-40 – Rpm control

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22 Day 4 Review

On the basis of which specification are electrical networks installed in the vehicle?

What does the intermediate circuit of a power electronics (DC/AC converter) do?

How is electrical work calculated and what can be determined with this?

How do you change the direction of rotation on an electric machine?

How is the speed and power output controlled on a three phase AC motor?

Which stator configuration is more powerful? More efficient?

How is an electric machine basically structured? (components involved)

How can an electric machine/stator be configured and what are the phase designations?

Explain the relationship between phase/conductor values vs. string values of a Star

Explain the relationship between phase/conductor values vs. string values of a Delta

23 List of Abbreviations

Terms

AC	Alternating current
TAR	Tasks, authority and responsibilities
ArbSchG	German Occupational Safety and Health Act
AuS	Working under voltage
BetrSichV	Occupational Safety Ordinance
BGV	Trade association regulations
CENELEC	Comité Européen de Normalisation Électrotechnique (English: European Committee for Electrotechnical Standardization)
CO_2	Carbon dioxide
DC	Direct current
DIN	Deutsches Institut für Normung (German Institute of Standardization)
DGUV	German Statutory Accident Insurance Association
ECE	United Nations Economic Commission for Europe
EFK	Electrically skilled person
EFKffT	Electrically skilled person for defined tasks
EFKmF	Electrically skilled person with technical responsibility
EHV	Expert for high-voltage systems in motor vehicles
EN	European standard
EuP	Electrically instructed person
EVA	Electric Vehicle Architecture
FfHV	Specialist for high-voltage systems
FHV	High-voltage competent person
FuP	Expertly instructed Person
GND	Ground
GTLS	Global Training Learning System
GWP	Global Warming Potential
HV	High voltage
HV+	High-voltage positive terminal
HV-	High-voltage negative terminal
ICCB	In-cable control box
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
Kfz	Motor vehicle
L1, L2, L3	External conductors in the 3-phase system
LED	Light-emitting diode

MPC	Market Performance Center
N	Neutral conductor
NTC resistor	Negative Temperature Coefficient Thermistor (hot conductor)
PE	Protective earth
PPE	Personal protective equipment
PTC resistor	Positive Temperature Coefficient Thermistor (cold conductor)
RCD	Residual Current Device (fault current circuit breaker or FI circuit breaker)
RMS	Root Mean Square
SGB	German Social Code
SoP	Start of Production
TRBS	Technical rules for operational safety
TRMS	True Root Mean Square
VDE	Association of Electrical Engineering Electronics Information Technology e. V.
VEFK	Responsible electrically skilled person
WIS	Workshop Information System

Physical variables

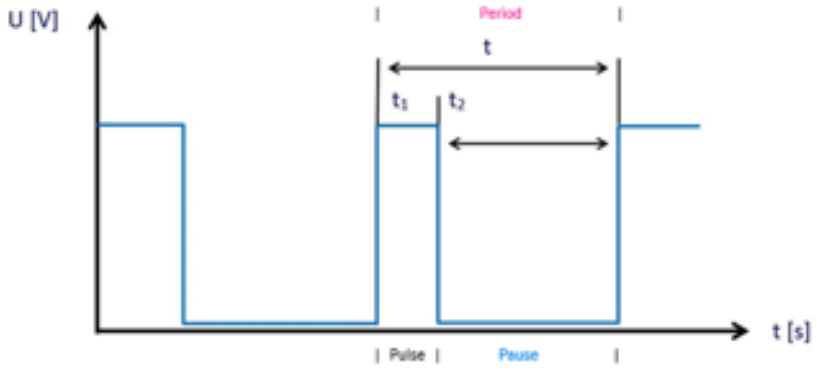
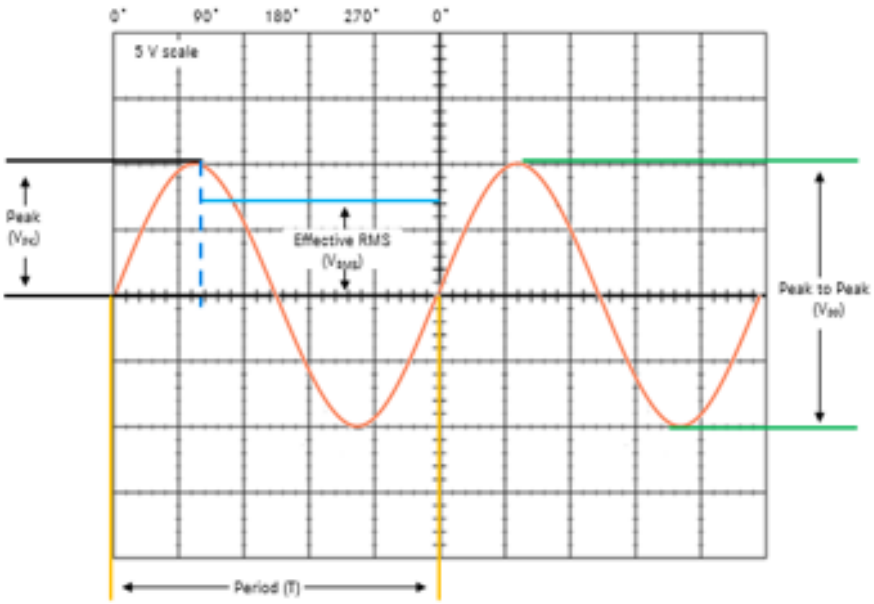
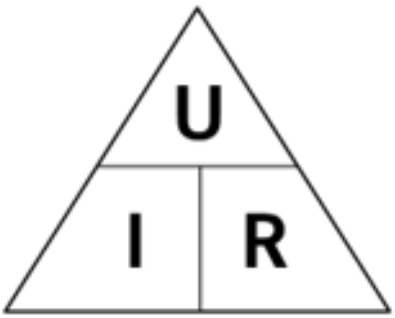
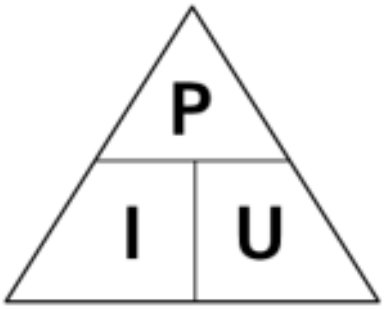
Formula symbol	Name	Unit	Unit symbol
C	Capacitance	Farad	F
E	Energy	Joule	J
f	Frequency	Hertz	Hz
I	Current strength	Amps	A
P	Power	Watt	w
Q	Charge	Coulomb	C
R	Resistance	Ohms	Ω
t	Time	Second	s
U	Voltage	Volt	V
W	Work	Joule	J

RMS Voltage - Peak Voltage x .707

Capacitor Charge/Discharge - 5T T = R x C or 5(R x C)

Three-Phase Power - (Apparent) $\sqrt{3}$ x U x I

(Active) $\sqrt{3}$ x U x I x cos

Electrical Work - U x I x t

	Conductor current	Conductor voltage	String current
Star connection	$I = I_{Str}$	$U = \sqrt{3} \times U_{Str}$	$I_{Str} = U_{Str}/R_{Str}$
Delta connection	$I = \sqrt{3} \times I_{Str}$	$U = U_{Str}$	$I_{Str} = U_{Str}/R_{Str}$